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Langley Research Center
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L1250

SUMMARY

The rendezvous of a pilot-controlled space ferry vehicle with an orbiting space station was simulated in six degrees of freedom. A fixed-base simulator and an analog computer were used. The ferry vehicle was assumed to have a single main thrusting rocket and to be provided with attitude control. Control of the thrust was provided by a rocket throttle quadrant which could provide either proportional or on-off control. The attitude of the vehicle was controlled during the rendezvous with a two-axis, pencil-type side-arm controller and rudder pedals. For the most part rendezvous maneuvers were made with the target satellite in a circular orbit. In addition, an elliptical station orbit was investigated. Tolerable initial conditions, as well as adequate data presentations, were determined.

Results of the investigation indicate that a human pilot can rendezvous successfully with the vehicle and instrumentation considered over a wide band of initial conditions. Coplanar conditions are not necessary. Retro-rocket fuel used is not greatly increased by imposing perturbing influences such as rocket-misalinement torques on the rendezvous vehicle. When excessive attitude-control torques are required to maintain the necessary trim attitudes under misalinement influences, the reaction fuel used for this control increases. The time required for a specific rendezvous varies somewhat between pilots. If control of the time for completing the rendezvous is desired, requirements for retro-rocket fuel are affected, and an energy-management schedule is required. Continuous variation of the thrust is not necessary. The pilot positions the throttle to obtain a desired level of thrust, and applies bursts of thrust as required.

All data were presented on dialed instruments. The quantities required are range and range rate and line-of-sight rates between the vehicle and the station, vehicle attitudes and angular rates, and the angles subtended by the line of sight. For the equipment assumed herein, satellite rendezvous presented no great problem to the pilot.

INTRODUCTION

A space rendezvous, involving human occupants of the vehicles involved, will be required in some phases of many space missions. Examples are the supply of a manned space station or a secondary-launch platform in an earth orbit. In these cases, rendezvous would be required for the rotation and recovery of personnel, as well as for buildup of equipment in the orbit because of booster limitations.

Previous studies have been made of the rendezvous and related problems. Reference 1 presents an analytical study which was conducted to determine boundary conditions for launching the ferry vehicle into the proper position to initiate the terminal rendezvous phase. The study presented in reference 2 concluded that the coplanar rendezvous is in the realm of human-pilot capability. Reference 3 is a simulation study of precision attitude-control tasks in space, performed by a human pilot. The simulation presented in reference 4 was limited to coplanar rendezvous within a half-mile range and used a simulated visual display. References 5 to 8 cover other such investigations.

The purpose of the present investigation is to determine the ability of a human pilot, given line-of-sight information on an instrument panel and reasonable vehicle dynamics in six degrees of freedom, to effect successfully the terminal phase of a satellite rendezvous. This study can be considered an extension of the work of references 2 and 4 in additional degrees of freedom, with consideration of some of the problems encountered in reference 3. The test runs were made by two NASA test pilots and a research engineer who has had piloting experience.

The present program was concerned only with the terminal phase of the rendezvous problem and the attendant difficulties presented to the human-pilot operator. A fixed-base simulator presented data to the pilot and allowed him to control the ferry vehicle to the space station to effect rendezvous. The loop was closed around an analog computer which solved the equations of motion, including vehicle dynamics and first-order approximations of the gravity field. Guidance and launch conditions were such that the path of the ferry was not necessarily coplanar with the space-station orbit. The terminal phase was assumed to start within 50 miles of the rendezvous point.

A realistic vehicle configuration, having six degrees of freedom and capable of traversing the launch, orbital, rendezvous, and reentry phases of a space mission, is assumed for this study. A single conventional rocket is assumed for thrust. Pure rotational reaction controls are assumed for attitude and are used for alining thrust in the proper direction. Display panels were designed to be compatible with all phases of the mission and to minimize instrument requirements.

SYMBOLS

The British system of units is used in this study. In case conversion to metric units is desired, the following relations apply:

1 foot = 0.3048 meter

1 statute mile = 5,280 feet

L1250

b	distance from thrust nozzle to vehicle center of gravity, ft
F	forces exclusive of gravity acting on the vehicle, lb
G	universal gravitational constant
$\bar{i},\bar{j},\bar{k}$	unit vectors
I	principle moment of inertia, slug-ft^2
K	gain
m	instantaneous mass of ferry vehicle, slugs
m_e	mass of the earth, slugs
M_x,M_y,M_z	moments about ferry body axes produced by altitude controls, ft-lb
R	distance along line of sight from space station to ferry, statute miles or ft
τ	time constant obtained by rate feedback, sec
T	rocket thrust, lb
ΔW	weight of fuel used by main rocket, lb
x,y,z	coordinates of ferry vehicle
X,Y,Z	axes fixed in space with origin in space station
α	angle subtended by line of sight between space station and ferry vehicle and projection of line of sight in X_I,Y_I plane, deg
β	angle between X_I-axis and projection of line of sight in X_I,Y_I plane, deg

ϵ angle of retro-rocket thrust misalinement, deg

ρ distance from the center of earth to orbiting space station, ft

$\bar{\sigma}$ position of ferry vehicle in a coordinate system with origin at earth's center and axes always parallel to lines fixed in an inertial frame, ft

ϕ,θ,ψ roll, pitch, and yaw angles, respectively, deg

p,q,r roll, pitch, and yaw rates about body x-, y-, and z-axes, respectively, deg/sec

Subscripts:

δ referenced to controller deflection

I relative to inertial axes

x,y,z relative to body axes of vehicle

X,Y,Z relative to space-station axes

A bar over a quantity denotes a vector.

A dot over a quantity denotes first derivative with respect to time; two dots denote a second derivative with respect to time.

DESCRIPTION OF THE RENDEZVOUS PROGRAM

Equations of Motion

Figure 1 illustrates the geometric relation between the rendezvous vehicle and the space station. The orbit of the space station (moving in a counterclockwise direction) and a typical direct-launch trajectory for the ferry vehicle are shown. A set of inertial axes, having the origin located at the center of the earth and the directions fixed with respect to the stars, form the basic coordinate system. This axis system shows the vectors $\bar{\rho}$ and $\bar{\sigma}$, the position vectors from the center of the earth to the station and to the ferry vehicle, respectively. The position $\bar{R}$ of the vehicle relative to the station is also illustrated.

In order to simplify the computation required to obtain $\bar{R}$ and to include the gravity terms in the computation, a mathematical derivation of the equations similar to the one in reference 5 is used to describe the relation between the ferry vehicle and the space station. The equation of motion when referenced to inertial coordinates with the origin at the center of the earth is given as:

$$\ddot{\bar{\sigma}} = \frac{\bar{F}}{m} - \frac{Gm_e}{\sigma^3}\bar{\sigma} \tag{1}$$

where

$$\bar{\sigma} = \bar{\rho} + \bar{R} \tag{2}$$

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and

$\frac{Gm_e}{\sigma^3}\bar{\sigma}$ gravitational acceleration

$\frac{\bar{F}}{m}$ acceleration due to the remaining forces, limited to main rocket thrust in the present study

In order to obtain the range R as a function of the forces and the station distance ρ, equation (2) is substituted in equation (1). If no forces other than the gravity force are assumed to act on the station, the resultant equation can be expanded in a Taylor series. Retaining only the lower-order terms and assuming that $R \ll \rho$ yields the resulting equation

$$\ddot{\bar{R}} = \frac{\bar{F}}{m} - \frac{Gm_e}{\rho^3}\left(\bar{R} - 3\,\frac{\bar{\rho}\cdot\bar{R}}{\rho^2}\,\bar{\rho}\right) \tag{3}$$

which is shown as equation (10) in reference 5. In order to simplify this equation, the orbit of the space station is assumed to be in the X_I,Z_I plane; components of the various parameters in inertial axes are, therefore,

$$\bar{\rho} = \bar{i}\rho_{X,I} + \bar{k}\rho_{Z,I} \tag{4}$$

$$\bar{R} = \bar{i}x_I + \bar{j}y_I + \bar{k}z_I \tag{5}$$

$$\bar{F} = \bar{i}F_{X,I} + \bar{j}F_{Y,I} + \bar{k}F_{Z,I} \tag{6}$$

Substituting equations (4), (5), and (6) into equation (3) yields the component accelerations, as follows:

$$\ddot{x}_I = \frac{F_{X,I}}{m} - \frac{Gm_e}{\rho^3}\left[x_I - \frac{3\left(\rho_{X,I}x_I + \rho_{Z,I}z_I\right)}{\rho^2}\rho_{X,I}\right] \tag{7}$$

$$\ddot{y}_I = \frac{F_{Y,I}}{m} - \frac{Gm_e}{\rho^3}y_I \tag{8}$$

$$\ddot{z}_I = \frac{F_{Z,I}}{m} - \frac{Gm_e}{\rho^3}\left[z_I - \frac{3\left(\rho_{X,I}x_I + \rho_{Z,I}z_I\right)}{\rho^2}\rho_{Z,I}\right] \tag{9}$$

L1250

In equations (7) to (9) the gravitational accelerations are given as functions of the distances $\bar{R}$ and $\bar{\rho}$. Since $\bar{\rho}$ is related to the space-station orbit only, it is a function of time and can be readily obtained from any assumed orbital conditions.

For solutions of equations (7) to (9), the thrusting forces must be resolved into the inertial axis system. These forces are obtained from the body forces by means of the conventional Euler angle conversions (ref. 9), where the order of rotation is taken as ψ, θ, and ϕ:

$$\begin{Bmatrix} F_{X,I} \\ F_{Y,I} \\ F_{Z,I} \end{Bmatrix} = \begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix} \tag{10}$$

The need for this order in ψ, θ, ϕ is explained in the appendix.

Once a station orbit is assumed, it is possible to solve the resulting equations (7) to (9) and to obtain the relative distance $\bar{R}$. It is assumed that the spacecraft used as the ferry vehicle has the capabilities of performing reentry and landing maneuvers. As noted previously, the vehicle is assumed to have a single rocket engine, which was alined with its body x-axis. Therefore, the forces F_y and F_z can be neglected in equation (10).

Before the Euler angles can be obtained, the rotational accelerations of the body axes must be computed. These accelerations are:

$$\dot{p} = K_{\delta,x} \frac{M_x}{I_x} - \frac{I_z - I_y}{I_x} qr - K \frac{M_x p}{I_x} \tag{11}$$

$$\dot{q} = K_{\delta,y} \frac{M_y}{I_y} - \frac{I_x - I_z}{I_y} pr - K \frac{M_y q}{I_y} + \frac{Tb\epsilon}{I_y} \tag{12}$$

$$\dot{r} = K_{\delta,z} \frac{M_z}{I_z} - \frac{I_y - I_x}{I_z} pq - K \frac{M_z r}{I_z} + \frac{Tb\epsilon}{I_z} \tag{13}$$

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The terms M_x, M_y, and M_z represent pure couples. The values of K_δ are functions of the attitude-controller deflections (unity for on-off control). The second terms represent the inertia coupling of the vehicle. For the problem herein it is assumed that $I_z = I_y$, which eliminates the inertia coupling term from equation (11). The third terms are representative of the artificial damping produced by a feedback system where K is the system gain and the quantity I/KM in each equation represents the time constant τ of the damped system response. The remaining terms in equations (12) and (13) are the thrust-misalinement terms, where ϵ is the thrust misalinement angle (up to 2.8°), and b is the arm from the center of gravity to the thrust nozzle.

The body angular rates can be computed by integrating these acceleration equations, and the resulting expressions can be used to define the Euler angle rates given by:

$$\dot{\psi} = \frac{q \sin \phi + r \cos \phi}{\cos \theta} \tag{14}$$

$$\dot{\theta} = q \cos \phi - r \sin \phi \tag{15}$$

$$\dot{\phi} = p + \dot{\psi} \sin \theta \tag{16}$$

These equations can be integrated to obtain the Euler angles.

As is shown in succeeding sections, it is necessary to obtain the relations between the vehicle and the space station in spherical as well as in Cartesian coordinates. Figure 2 shows the spherical and Cartesian relations between the ferry vehicle and the origin of the nonrotating axis system in the space station, as well as the Euler angles of the vehicle. From figure 2 it can be seen that:

$$\beta = \tan^{-1} \frac{y_I}{x_I} \tag{17}$$

$$\alpha = \tan^{-1} \frac{z_I}{\sqrt{{x_I}^2 + {y_I}^2}} \tag{18}$$

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$$R = \sqrt{{x_I}^2 + {y_I}^2 + {z_I}^2} \tag{19}$$

The rates of change of these quantities with respect to time are obtained by differentiation and substitution of the following spherical conversion equations:

$$x_I = R \cos \alpha \cos \beta \tag{20}$$

$$y_I = R \cos \alpha \sin \beta \tag{21}$$

$$z_I = R \sin \alpha \tag{22}$$

which yield

$$\dot{\alpha} = \frac{\dot{z}_I}{R} \cos \alpha - \frac{\sin \alpha}{R}\left(\dot{x}_I \cos \beta + \dot{y}_I \sin \beta\right) \tag{23}$$

$$\dot{\beta} = \frac{\dot{y}_I \cos \beta - \dot{x}_I \sin \beta}{R \cos \alpha} \tag{24}$$

$$\dot{R} = \dot{z}_I \sin \alpha + \cos \alpha\left(\dot{x}_I \cos \beta + \dot{y}_I \sin \beta\right) \tag{25}$$

By solution of equations (7) to (16) and equations (23) to (25), it is possible to compute the angular attitudes and range between the space station and the ferry vehicle and the attitudes of the ferry vehicle with respect to a set of inertial coordinates. These equations were solved for the simulation study by use of an analog computer. The first-order terms of an expansion of the expression for gravity were included in the equations of motion.

Description of Rendezvous Procedure

The method used in the present investigation to effect a rendezvous was first to attain and then to maintain a collision course. Once on a collision course it is necessary to bring the relative velocity of the vehicle with respect to the station to zero at near-zero range. In an actual mission, docking could then be completed. Since the paths of the vehicle and the station are curved because of the forces of gravity, no single set of conditions can describe all collision courses, as would be true if the paths were straight lines. Instead, the collision-course conditions are a function of both the radial distance and the closing velocity. However, when both paths are similar and the distance between the vehicle and the space station is small with respect to the radius of curvature of the paths it is possible to approximate a collision course by making the following assumptions:

$$\dot{R} \text{ is negative}$$

$$\dot{\alpha} = 0$$

$$\dot{\beta} = 0$$

Reference 1 supports this assumption and points out that $\dot{R}$ remains nearly constant during the terminal phase if no braking thrust is applied. The present investigation is directed toward determining to what degree this approximation can be used by a human operator to effect a rendezvous.

The general conditions for rendezvous at the end of a direct launch have been investigated (ref. 1). From the results of reference 1, the relative closing velocity in a 300-mile orbit, for a range of less than 50 miles, is estimated to be between 400 ft/sec and 1,000 ft/sec.

Since the ferry vehicle is at its apogee, as illustrated in figure 1, it is moving more slowly than the station and thus, if on a collision course, is ahead of the station. Therefore, x_I will generally be positive, while y_I and z_I can be either positive or negative. Likewise, $\dot{\alpha}$ and $\dot{\beta}$ could have any initial value depending on the accuracy of the injection conditions and any midcourse corrections.

With these conditions in mind, a realistic rendezvous problem can be posed as follows: Injection guidance places the ferry vehicle so that it will come to within approximately 50 miles of the station, or close enough to attain direct electronic "lock-on" with the station. At this point the pilot of the ferry vehicle, having line-of-sight and range information, attempts to perform the remainder of the rendezvous. The pilot's task can be divided into two parts. First, he must get on an approximate collision course by thrusting to make line-of-sight rates zero. Once on a collision course this condition must be maintained because, as a result of the slight orbital curvature relative to the chosen axis system, the vehicle will deviate from this collision course. The second part of the pilot's task is to effect a braking action so that the relative velocity is reduced to zero at near-zero range. Although this maneuver is considered a braking action relative to the space station, it actually provides a force which speeds up the ferry vehicle to the orbital velocity of the space station when viewed from the inertial axis system. The criterion for a successful maneuver in the present study is satisfied if range is below 1/4 mile when range rate is arrested. Runs were also made wherein range and range rate were both brought to zero.

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In order to illustrate the piloting procedure required to perform the first phase of the rendezvous, the supposition was made that there existed some line-of-sight rates $\dot{\alpha}$ and $\dot{\beta}$. (See fig. 2.) To bring either $\dot{\alpha}$ or $\dot{\beta}$ to zero would require pitching or yawing the ferry 90° to the flight path and removing the component of velocity normal to the line of sight. This maneuver would place the vehicle on a collision course toward the space station. Once a collision course is attained, small corrections will be required to maintain zero $\dot{\alpha}$ and $\dot{\beta}$. It can be seen in figure 2, however, that when the vehicle is yawed 90° to make a thrusting correction for $\dot{\beta}$, θ is not necessarily zero and consequently the trigonometric relations are such that the thrust axis is not exactly perpendicular to the line of sight. This circumstance will create a change in $\dot{R}$ and $\dot{\alpha}$. In an actual rendezvous the pilot would initially aline the x_I-axis within a few degrees of the line of sight, so that the tilting of the perpendicular correction plane is minimized. In this study the initial position of the x_I-axis was not taken along the line of sight, but rather was taken horizontal because the intent was to have gravity and noncoplanar effects accurately simulated.

In the second phase of the rendezvous the pilot is required to provide a braking action. If the pilot is assumed to be on a collision course, it is necessary that his thrust vector be pointed along the line of sight. This position may be accomplished by yawing the ferry so that

$$\psi = -\beta$$

and pitching the ferry so that

$$\theta = \alpha$$

Thrust must then be applied so that $\dot{R}$ becomes zero when $R < \frac{1}{4}$ mile. In the majority of the runs simulated, the α and β dials were used as combination instruments to display $\theta - \alpha$ and $\psi + \beta$ as a means of simplifying the task of the pilot in pointing the thrust vector along the line of sight without having to cross reference two pairs of instruments.

In practice a type of energy management technique was used in which values of range were matched with closing speed so as to provide slower closure rates at close-in range. A schedule of matching range and range rate that proved helpful during these tests is presented in a subsequent section.

The present program was conducted to determine whether this straightforward technique would be sufficient, within the 50-mile limit, to enable a pilot to effect a rendezvous, as well as to determine which instrument display would allow him to do the problem effectively.

DESCRIPTION OF EQUIPMENT

An analog computer was used to solve the equations of motion. A photograph of the computer and the basic simulator are presented in figure 3. The simulator consisted of a fixed chair, an instrument panel, rudder pedals, a side-arm reaction controller, and a throttle. A view of the cockpit is shown as figure 4.

Data Displays

Two basic instrument panels were used as data displays in the present program. Preliminary rendezvous maneuvers were executed with each of the displays in various stages of development. Essentially the same quantities were presented on panels 1 and 2. The major difference was that two bits of information, either R and $\dot{R}$ or $\dot{\alpha}$ and $\dot{\beta}$, were shown on the oscilloscope in panel 1. Two versions of panel 1 were used. The first version showed ordinate values of $\dot{R}$ and abcissa values of R. The station remained fixed at the origin of the range—range-rate axis system, and the ferry was below and to the right of the station in accordance with the initial conditions. As R and $\dot{R}$ were attenuated during the rendezvous maneuver, the pilot could choose one of four values of deceleration for final rendezvous. These trajectories were curved paths to the station etched on the high-persistence cathode-ray tube by a sweeping dot. The slope of the sweep was directly proportional to the constant thrust level that would be required to bring R and $\dot{R}$ to zero simultaneously. The selector switch to the left of the oscilloscope was labeled in 1/4-thrust steps. If the pilot chose $T/4$ and overshot that trajectory shown on the oscilloscope, he could switch to the next level of $T/2$ and attempt to home in on that path firing half thrust, and so on. When R and $\dot{R}$ were presented on the oscilloscope, the line-of-sight rates $\dot{\alpha}$ and $\dot{\beta}$ were on dials. The second version of panel 1 may be seen in figure 3, a closeup is presented in figure 5, and the two oscilloscope layouts are illustrated in figure 6.

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The version of display panel 1 which presented $\dot{R}$ against R on the oscilloscope (fig. 6(a)) was suggested by other work being done on automatic rendezvous, but this panel did not prove to be satisfactory for the present study. It was felt that the oscilloscope could be used to better advantage if $\dot{\alpha}$ and $\dot{\beta}$ were displayed; therefore, the version that showed the ferry moving on a grid as a function of line-of-sight rates $\dot{\alpha}$ and $\dot{\beta}$ was instrumented (fig. 6(b)). This version was satisfactory as a rough means of controlling the collision course, but was very difficult to use at short range because of a minimum sensitivity of 1 milliradian per second and was abandoned for the all-dial presentation.

The results of this preliminary experience with visual displays showed the need for more realism in this type of presentation, and the remainder of the program was carried out with dialed instrument display panel 2 (fig. 4).

All instruments on the panel shown in figure 4 are in the zero position. From left to right in the top row the first instrument indicates the angle β (or $\psi + \beta$ when combined), the second indicates $\dot{\alpha}$ by movements of the horizontal needle and $\dot{\beta}$ by movements of the vertical needle, and the third instrument indicates the angle α (or $\theta - \alpha$ when combined). The first two instruments in the second row indicate attitude angles, yaw angle on the first, and pitch and roll on the two-axis "8-ball." Directly below the 8-ball are the three body-axis angular velocities; roll rate p is indicated by the vertical needle on top, pitch rate q by the horizontal needle, and yaw rate r by the bottom vertical needle. To the right of the 8-ball is the relative-velocity indicator showing range rate, and directly below this is the range indicator. To the side of these are two change-of-scale switches which reduce the range-rate and range scales by a factor of 10, thus giving more sensitive readings at closer range and slower velocities. Full-scale readings for these range and range-rate dials were 50 miles and 900 ft/sec on high scale, and 5 miles and 90 ft/sec on low scale, respectively.

Available instruments are adequate for all the display accuracies assumed herein except the line-of-sight rates $\dot{\alpha}$ and $\dot{\beta}$. Full-scale deflection of the instrument for $\dot{\alpha}$ and $\dot{\beta}$ represented ±1 milliradian per second. This sensitivity is desirable early in the rendezvous for fuel economy and accurate navigation. In the present state of the art, airborne radar systems have angular rate inaccuracies up to the full-scale deflection of the instrument assumed. The need is shown for either improved radar and signal smoothing or optical tracking devices.

L1250

Throttle

The throttle was a proportional standard aircraft type to which were added four detents which represented accelerations of 0.1g, 0.2g, 0.3g, and 0.4g when thrust was provided. In order to obtain a certain thrust level, the pilot would move the throttle to the desired level and push a switch on top of the throttle for continuous thrust or a button on the side of the throttle for intermittent thrust.

Controls

The side-arm controller used in this investigation controlled pitch and roll. Four springs in tension were used for centering the stick with no intentional friction. The springs had a nearly linear force gradient of 0.7 pound per inch. This gradient represented a force of 0.5-pound-per-inch deflection at the top of the stick. Total deflection was 2 inches. Two springs in tension were used to center the rudder pedals. The springs had a near-linear force gradient of 5.5 pounds per inch. The pedals rotated independently about a pivot at the pilot's instep. Each pedal deflected forward 23°, which extended the centering spring 2 inches and required 4 foot-pounds of torque for full deflection.

As stated in the section on "Description of the Rendezvous Procedure," the pilot must match ψ with $-\beta$ and θ with α in order to aline the thrust vector of the ferry vehicle along the line of sight to the station for maximum braking. The use of the two instruments that sum $\psi + \beta$ and $\theta - \alpha$ greatly simplifies this maneuver. Early data runs were made with and without the combination instruments to evaluate them. These combination instruments proved to be very helpful in the final rendezvous phase and under severe conditions, and were therefore used in the remainder of the tests.

TESTS

The rendezvous runs presented herein were made by three pilots identified as pilots A, B, and C; two were NASA test pilots and the third was a research engineer who was formerly a military pilot. The equations representing the relative motions of the rendezvousing vehicles were solved by a general-purpose analog computer. Signals representing these spatial quantities were fed by the computer to the pilot's instrument panel. The pilot responded to the instruments and made attitude and displacement inputs to the controls of the space ferry to effect rendezvous. These maneuvers by the pilot were fed back to the analog computer as inputs to the machine elements solving the equations of motion and thereby completing the servomechanism loop.

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Initial Conditions

Six sets of initial conditions, or cases, representing direct-launch trajectories, were used in making the study. The conditions existing at the beginning of rendezvous for the six cases, along with the approximate miss distances that would occur if no corrections were made, are listed in table 1. The cases are arranged in order of increasing difficulty. For the conditions of cases 1 to 5, there was some initial relative velocity between the ferry vehicle and the orbiting target station. Case 6 represented a special near-orbital condition with essentially zero relative velocity. The straight-line assumptions used would not allow calculation of miss distance for case 6.

By reference to figure 2, which identifies the coordinate system of the ferry vehicle relative to the space station, the six cases listed in table 1 are described. Case 1 shows the ferry vehicle 30 miles in front of and above the station at a coplanar elevation angle α of 45° and moving 495 ft/sec slower than the orbiting station as measured along the line-of-sight vector $\bar{R}$. This line-of-sight vector is also rotating in the orbital plane at a rate of 0.0284° per second, which, if not arrested, will increase α until the ferry passes over the station. In order to effect a rendezvous, the ferry must pitch down and fire the retro-rocket until $\dot{\alpha}$ is zero. Then closure between the ferry and the station will be along the line-of-sight vector $\bar{R}$. If the station is considered fixed, and the body-axis angle θ of the ferry is zero, then the ferry is traveling backward down the line of sight to the station with its retro-rocket point horizontal or 45° above the line of sight; therefore, if the retro-rocket is to be used for braking, the ferry must be pitched up 45° to point the thrust vector at the target.

Case 2 places the ferry at the same altitude as the station but 50 miles in front and to the right at $\beta = -22^{\circ}$ and β increasing at -0.054° per second. Rendezvous in this case can be made by turning left, firing the retro-rocket to bring $\dot{\beta}$ to zero, and then making subsequent braking thrusts along the line of sight by maintaining a yaw angle to the right to match $-\beta$ so that the resultant thrust is toward the station. A similar procedure would be required for cases 3 to 5. It can be observed from table 1 that the initial conditions generally give the position of the vehicles for a range from 10 to 50 miles and in the hemisphere where the vehicle is ahead of (but not necessarily coplanar with) the station. Range rates of -4.3 to -875 ft/sec are covered.

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Case 6 is for a special near-orbital condition that places the ferry 30 miles in front of the station and 20° above and 20° to the left, but with a range rate only 4.3 ft/sec slower than the station velocity. For rendezvous to be accomplished under these initial conditions, the ferry has to be yawed 160° to the right and pitched down 20° to point the nose of the ferry toward the station and create a closing speed by thrusting along the line of sight. After the desired relative velocity is obtained, the pilot turns the rocket toward the station and proceeds to rendezvous as in the other cases.

Vehicle Parameters

The mass of the ferry vehicle was assumed to be 124 slugs, with a moment of inertia about the x-axis of 450 slug-ft^2 and equal moments of inertia about the y and z axes of 4,500 slug-ft^2. Rocket thrust along the x-axis was 1,600 pounds at full throttle to provide a maximum acceleration of 0.4g. The throttle provided a linear variation of acceleration from 0g to 0.4g, with detents at levels of 0.1g, 0.2g, 0.3g, and 0.4g, and the rocket had multistart capability. During the present tests the pilots used on-off thrust by choosing the desired acceleration level and either moving a switch on top of the throttle (for extended firing) or pressing a button on the side of the throttle. Variable thrust during rocket firing was not required. Usually 0.2g was used at the beginning of a rendezvous run for rapid spatial corrections, and then the throttle was retarded to 0.1g or lower for close-in braking of the final rendezvous phase. The rocket-nozzle exit plane was 11 feet behind the center of gravity of the ferry vehicle.

Pure rotational jet-reaction control couples provided attitude control of the ferry vehicle. The maximum control moments were 220 foot-pounds in yaw, 180 foot-pounds in pitch, and 35 foot-pounds in roll, and resulted in angular accelerations of 2.8, 2.3, and 4.5 deg/sec^2, respectively. The attitude forces were linear with control movement for the data presented herein. During the tests, on-off attitude controls were also investigated by having the controls command full torque when deflected beyond a $\pm 2^{\circ}$ dead zone. The use of on-off controls did not affect the ability of the pilot to orient the ferry for rendezvous maneuvers with the control torques used. Actually, the majority of the controller motions made by the pilots with proportional control were pulses of an on-off nature. Thus, the maximum rotational accelerations were usually commanded in an on-off manner when rotating the ferry, and proportional control was not required. The instrument that showed body-axis rates p, q, and r was especially helpful for monitoring angular maneuvers.

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Artificial damping was provided for the ferry vehicle by control-loop feedbacks which produced reaction torques proportional to body rates. The amount of damping in roll, pitch, and yaw was determined by time-constant gains τ_x, τ_y, and τ_z, respectively. (See eqs. (11) to (13).) Light damping was furnished by 10-second time constants, and rather heavy damping resulted from a time constant of 2 seconds. The system had no restoring moment, and the damping produced by these rate-controlled counter thrusts was not oscillatory, regardless of the damping level, but reduced vehicle rates smoothly to zero.. Thrust misalinements were investigated during the tests. Moments caused by thrust components normal to the body X-axis were produced by a rocket misalinement angle ϵ relative to the x,y and x,z planes. This angle ϵ was 0.25° for misalinement data presented herein unless noted otherwise. When 0.1g of acceleration was applied, the 0.25° misalinement of the rocket produced a disturbing moment of 35 foot-pounds in yaw and pitch. The pilots were naturally conservative with rocket thrust when this 0.25° rocket misalinement existed. Successful runs were also made with a rocket misalinement of 2.8° in yaw and 2.2° in pitch that produced yawing and pitching moments which required 90 percent of the control capability to overcome.

RESULTS AND DISCUSSION

Typical Rendezvous

Figure 7 presents a typical rendezvous made by pilot B with the conditions given in table 2 for case 4 showing a time history of R, $\dot{R}$, ΔW, α, β, θ, ψ, T/m, yaw and pitch control in foot-pounds of reaction control moment, x_I, and y_I. It can be seen that the pilot chose to reduce the closing speed by about half during the first portion of the run, thrusting at the relatively high level of 0.2g for the first 200 seconds. About 2/3 of the total fuel ΔW used for the rendezvous was used during this period. At the same time, the attitude of the ferry in pitch and yaw was controlled so as to utilize this initial thrust to bring $\dot{\alpha}$ and $\dot{\beta}$ to zero and place the vehicle on a collision course toward the station. Since the vehicle dynamics included some damping and had no disturbing torques due to rocket misalinement, the attitude-control inputs were generally the same over the entire run. No attempt was made to correct for the elevation angle α and the out-of-plane angle β, and the angles, after being altered slightly before their angular rates were arrested during the first 200 seconds, remained fairly constant during the rendezvous. It was pointed out in the previous section on "Description of the Rendezvous Procedure" that a correction for $\dot{\beta}$ produces a change in $\dot{\alpha}$ and $\dot{R}$ when the correction plane is not exactly perpendicular to the line of sight. This effect on $\dot{R}$ and $\dot{\alpha}$ caused very little trouble in the present simulation.

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After obtaining a course for intercept, figure 7 indicates that the pilot chose to retard the linear throttle control to about 1/3 the initial setting and then followed a consistent pattern of orienting the retro-rocket and firing thrust by pressing the throttle button to maintain the collision course and reduce the speed of closure. The number of steps in the thrust trace and the number of control inputs to yaw and pitch are a measure of the frequency of corrections to line-of-sight and range rates considered necessary by the pilot. The consistent manner in which x_I and y_I approached zero, and the fact that R was between 1/4 mile and zero when $\dot{R}$ became zero, indicated that the criterion for a successful rendezvous was met. The recorded data for the rendezvous maneuvers, such as those reproduced in figure 7, cannot be read to the same degree of accuracy as the pilot's instruments. For example, the range trace in figure 7 can only be read to within about 5 miles; whereas the pilot's instrument, which was set to a more sensitive scale, could be read to less than 0.2 mile. Tests were also made wherein both range and range rate were brought to zero. The zero readings on the R and $\dot{R}$ instruments were verified by the computer operator. The single thrusting rocket with linear thrust control was satisfactory for this docking phase, but the final 1/4 mile required another 2 to 4 minutes.

Lack of Correlation Between Pilot Opinion and Work Load

Table 2 shows a standard schedule of pilots' opinions used to rate the vehicle control characteristics for each rendezvous run. A portion of the bar graph in figure 8 shows the average pilot-opinion rating for control characteristics as given in table 2 for several runs made at each initial-condition case. These control ratings cover runs with and without damping and with and without thrust misalinement. Figure 8 does not include special runs entailing excessive amounts of misalinement or minimum thrust. In general, each case studied shows no appreciable change in task difficulty, as illustrated by averaged pilot opinion ratings in figure 8. However, when considering the separate effects of various damping and misalinement torque levels, a noticeable trend in pilot opinion is observed. By inspection, table 3 shows that as conditions vary from "with damping" and "no misalinement" to "no damping" and "misalinement," the averaged pilot rating goes from nearly "good" to nearly "unacceptable." It was concluded, however, that for the conditions investigated, on the average a pilot could perform a successful rendezvous.

Figure 8 also shows the number of attitude-control inputs made by the pilots per second for the first five cases; these were obtained by averaging the number of control inputs above a $\pm 2^{\circ}$ deflection of the
controller. The cases are arranged in the order of work load. A com- L
parison of the two parts of the bar graph in figure 8 indicates that 1
there was no definite correlation between the pilot-opinion ratings and 2
the specific control inputs for the conditions investigated. This lack 5
of correlation can be explained in part by the fact that the low control 0
forces required to operate the pencil-type side-located controller and the rudder pedals did not constitute a marginal work load and, in addition, by the fact that the conditions present in a general rendezvous fall in a wide band of tolerability, as shown by the pilot opinions.

Effect of Damper Failure and Thrust Misalinement

To illustrate how a successful rendezvous would be possible with damper failure or with large misalinement torques, runs were made under these conditions and time histories of the results are presented in figures 9 and 10, respectively. In figure 9, relatively heavy artificial damping with a 2-second τ was removed from all three axes 480 seconds after "lock-on" without causing undue trouble other than a slightly increased work load. No thrust misalinement was present for the run shown in figure 9. Although the pilots concurred that the present system could be controlled without damping if other conditions were not too severe, nevertheless their comments indicated that some damping was desirable.

In figure 10 a comparison between similar runs with and without thrust misalinement shows the effect of relatively high thrust misalinement torques. The runs simulated in figure 10 were made with damping, and the retro-rocket was misalined for figure 10(b) so as to produce a disturbing torque equal to 90 percent of the total attitude-control capability in pitch and yaw at the 0.1g thrust level used. It can be seen in figure 10(b) that the pilot had to control the vehicle about a new attitude-trim position equal to 90 percent of control travel while the retro-rocket was being fired. Even under this extreme condition, rendezvous was successful, because the pilot had the advantage of firing a burst at low thrust so as to identify disturbing torques and thus to make anticipatory corrections during later bursts.

Rendezvous Techniques

Figure 11 presents the position of y_I and z_I plotted against x_I defining the space trails for three pilots flying under the conditions of case 4 in table 1. It can be seen that except for the y_I trace of pilot C's position, the pilots tended to follow similar paths in space. This result indicates that generally it took each pilot about the same length of time to interpret the initial conditions and to make the necessary corrections to get on a collision course; throughout the investigation the three pilots used essentially the same techniques to make spatial corrections and control the vehicle to the target.

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Figure 12, on the other hand, shows how the time of run can vary when the same quantities presented in figure 11 are referred to the scale of time. Rendezvous with pilot A was effected in 800 seconds as compared with about 1,000 seconds with pilots B and C. This run for case 4 had damping and no misalinement, which made it an easy condition to control. When more stringent conditions existed, however, the variations in time to effect a rendezvous were even more pronounced. Each rendezvous technique had a specific effect on time. For example, a minimum-fuel rendezvous would tend to reduce the range rate to near zero while a collision course is being obtained, and rendezvous time would approach infinity; however, if a minimum-time rendezvous is desired, initial range rate would be preserved or even increased while a collision course is being obtained, and braking would be applied just prior to contact. All these factors emphasize the fact that, during intercept, the pilots' energy- and time-management techniques differ and that if time to effect a rendezvous is important, then further information must be presented to the pilot.

Figure 13 shows a suggested range—range-rate schedule that was set up from the experience of the pilots during these tests and this schedule is indicated by points joined by a dashed line. This information was presented to the pilots in the form of a table and proved helpful for monitoring these two variables during the present study so that the time to effect a rendezvous could be controlled and adequate control of the vehicle retained. This schedule was especially useful in the final 10 miles, or in the presence of low thrust or large misalinement torques. The exponential relationship between R and $\dot{R}$ as used in the present tests is modified for range greater than 1 mile in figure 13. In order to get on schedule, initial thrusting accelerations of at least 0.2g were used by the pilots, and after a collision course was acquired, lower thrust levels were used. Braking was made in steps, with time available between these step thrusts for the pilot to monitor the instruments and orient the vehicle. This procedure was found to be very satisfactory.

If a continuous constant acceleration is used, the expression $\dot{R} = (2aR)^{0.5}$ describes the relationship in figure 13 close to the station, where a is the acceleration in ft/sec^2, $\dot{R}$ is in ft/sec, and R is in feet. Thus, if a collision course is established, the value of acceleration along the line of sight is 0.018g. However, if the pilot attempts to maintain this low acceleration level, this technique requires constant scanning of the instruments and simultaneous attitude control for course correction. The time to rendezvous may be controlled more closely, but the piloting task is much more severe than the method of alternately orienting the vehicle and firing greater thrust in an on-off manner.

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Some runs were made with the initial conditions of case 5 wherein a constant low acceleration of 0.05g was utilized from the start and held constant for 82 percent of the run. This control procedure was found to be very difficult primarily because the instrument that presented $\dot{\alpha}$ and $\dot{\beta}$ to the pilot was against the stop during a large part of the run. This instrument had a maximum range of $\pm 0.057^{\circ}$ per second, and the pilot could recognize a rate 1/10 of this, or 0.0057° per second. Some runs were successfully completed when the computer operator verbally relayed the values of $\dot{\alpha}$ and $\dot{\beta}$ to the pilot while they were off scale. This result indicates that a rendezvous with constant, low acceleration might be completed if the instrument displaying $\dot{\alpha}$ and $\dot{\beta}$ had adequate range. A two-range instrument would provide this, as well as the high sensitivity that is required to maintain a collision course after it has been established. The limited range of the $\dot{\alpha}$ and $\dot{\beta}$ instrument was not a disadvantage when the intermittent, higher-thrust technique was used, because the values of $\dot{\alpha}$ and $\dot{\beta}$ could be rapidly reduced to near zero at the start of the run.

Fuel Use

Figure 14 shows a comparison of the amount of fuel used for each rendezvous case with the minimum required for that case. Fuel for rendezvous in minimum time is defined as the amount required to get on a collision course without changing $\dot{R}$ plus the amount required to bring $\dot{R}$ to zero. The reference minimum was calculated by assuming that a single burst of thrust would be used to decrease the relative velocity between the station and the vehicle to zero. Rendezvous would then be initiated by an infinitesimal thrust in the proper direction for closure. This type of procedure would make the time to rendezvous approach infinity. Actual fuel use was recorded. Fuel required ΔW was calculated by means of the relation:

$$\Delta W = W_o\left(1 - e^{\frac{-\Delta V}{I_{sp}g}}\right)$$

where the specific impulse I_{sp} was assumed to be 230 seconds, the g force referenced at sea level was 32.2 ft/sec^2, and the initial weight W_o was 4,000 pounds. The velocity increment ΔV for the minimum-time rendezvous was made up of two parts, the velocity normal to the flight path and the range rate. The figure indicates that in most cases the pilot was able to use fuel not too much greater than the minimum and on an average the amount of fuel was within a few percent of the minimum. The exception was case 2, with a relatively large range of 50 miles and the closure $\dot{R}$ only 435 ft/sec. This $\dot{R}$ would match about 15 miles range on the schedule shown in figure 13, and consequently for the first 35 miles of the rendezvous, tangential corrections to $\dot{\alpha}$ and $\dot{\beta}$ wasted fuel until range was on schedule with range rate. As an illustration of the time dependence, if reference is made to figure 12 where pilot A was shown to make the rendezvous in less time than pilots B and C, the fuel used as a function of time can be verified. Records show that pilot A used 622 pounds of fuel, while pilots B and C used less than 577 pounds each.

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It is interesting to note that severe operating conditions do not necessarily cause a large increase in fuel usage. Figure 10, which presented a time history of control motions and thrust for a severe misalinement torque, bears this out. Fuel required for the normal run of figure 10(a), recorded elsewhere, was 462.5 pounds, while fuel used for the run with 90-percent thrust misalinement in figure 10(b) was 550 pounds, or less than 20 percent more. On-off reaction attitude controls were also investigated during the tests, and retro-rocket fuel use was the same for a specific condition with those controls as with the proportional controls.

Special Cases

In order to investigate such effects as elliptical station trajectories, and near-zero initial closing rates, runs with special rendezvous conditions were made.

Case 6 of table 1 was a near-orbital condition, with essentially no initial closure between the vehicle and the space station, and with the station in a 300-mile circular orbit just as the five cases previously described. Figure 15 shows a time history of a typical run made for these conditions. Referring back to figure 7, it can be seen that with the exception of the need to rotate the vehicle in yaw to create closing speed, the run for case 6 followed the same pattern as for case 4. Thus it established that this near-orbital condition presented no problem to rendezvous with the present system. Figure 16 is a space-trail trajectory for case 6, and is comparable to figure 11 regarding similarity between piloting techniques. In this run pilot A was slower than pilots B and C to reverse the direction of the retro-rocket in order to speed up, as shown by the trajectory of x_I and z_I. As a result of the lag in orienting the vehicle initially, the time trails of x_I, y_I, and z_I in figure 17 for case 6 show that pilot A required more time to rendezvous than pilots B and C, which is the reverse of the comparison run shown in figure 12.

Another series of special runs was made to study the possibility of effecting a rendezvous with the station in an elliptical orbit. The initial conditions for the vehicle relative to the station were the same as for case 4, but the station orbit was elliptical with a 100-mile perigee and a 500-mile apogee. Rendezvous maneuvers were begun with the station at apogee. Figure 18, which shows the recorded variables for this condition, proves that the ellipticity of the target orbit presented no problem in making a rendezvous. The results in figure 18 are comparable with those of figure 7, which presented the same variables for case 4 in a circular station orbit.

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In order to study the difference between the actual line-of-sight trajectory and an uncontrolled rendezvous trajectory, and the manner in which the pilot compensates for this difference, several runs were made with the space station in an elliptic orbit wherein the ferry vehicle was placed on a line-of-sight course in the initial phase and then allowed to coast in the final phase without further flight-path corrections. Figure 19 shows two of these coasting space trajectories of z_I plotted against x_I compared with a rendezvous run that was controlled all the way. The high-speed run, in which 802 ft/sec closing velocity remained after getting on course at a range of 33 miles shows a miss distance of about 1 mile above the station. If the gravity field were not present, a straight-line error of less than the $\pm 1^{\circ}$ of the instrument sensitivity in establishing the collision course could account for this small miss distance. This much piloting or instrument error is of the same order as the difference between the true orbital trajectory and the chosen straight-line path between the ferry and the station. The low-speed run ($\dot{R}$ = 160 ft/sec) had 1/5 as much speed, coasted from 36 miles, and resulted in correspondingly greater accumulated miss distance, but it passed under the station. Figure 2 of reference 5 shows that the apparent gravity vector is in the same direction in the 1/8 of a station orbit that included both of the coasting runs shown in figure 19. The conclusion to be drawn from figure 19 is that the pilot does not permit the cumulative effects of both the gravity difference between the ferry and the station and the instrument error to build up, and therefore he does not notice that they cause any trouble. The free-fall trajectories in figure 19 were terminated when excessive line-of-sight rates overloaded the analog computer.

CONCLUSIONS

The results of the present investigation simulating the terminal phase of a ferry vehicle rendezvous with an orbiting space station indicate that:

1. A human pilot has the control capability to effect rendezvous successfully in the presence of relatively severe conditions if adequate vehicle control and flight-data presentation are provided.

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2. A single retro-rocket with multistart capabilities is sufficient for space control if universal attitude controls and display information on line-of-sight rates and range and range rate are furnished. Continuously variable rocket thrust is not necessary. Pilots preferred to use intermittent thrust of constant value. Thrust misalinements up to 90 percent of attitude-control capability can be handled.

3. The rendezvous vehicle need not be coplanar with the satellite station prior to rendezvous, and initial conditions, within a wide band of control capabilities of the vehicle, do not adversely affect rendezvous ability.

4. In the absence of visual aids, the instrument presentations that the pilots deemed necessary are as follows:

Range and range rate

Elevation and azimuth line-of-sight rates

Vehicle attitude angles

Vehicle attitude-angle rates

Elevation and azimuth angles

A change-of-scale switch that would provide two or more levels of sensitivity during the rendezvous maneuver would be desirable for the instruments which present $\dot{\alpha}$, $\dot{\beta}$, R, and $\dot{R}$.

5. Experienced pilots using dialed instruments tend to follow similar space trajectories in making a rendezvous, but times to rendezvous vary somewhat, and an energy-management schedule that could be presented to the pilot as a table or additional display would be required for time control. Pilots also tend to use moderate pitch and yaw angles to make corrections for line-of-sight rates $\dot{\alpha}$ and $\dot{\beta}$ at

the same time, which alters range rate. In order to maintain range rate, course correction must be made normal to the line of sight so that no thrust component is along the line of sight. The effects of curved vehicle paths and elliptical target orbits on the ability to rendezvous are negligible.

6. The average amount of fuel used by the pilots is usually only slightly more than the reference minimum. Perturbing effects, such as thrust-misalinement torques and on-off reaction controls do not necessarily cause an increase in fuel usage. Fuel use does vary moderately with specific rendezvous techniques controlling the time required.

7. Some artificial damping of the angular motions of the vehicle is found to be desirable but not essential.

8. There is no definite correlation between pilot opinions and attitude-control input frequencies for a wide band of tolerable control characteristics and data displays.

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Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., January 10, 1961.

APPENDIX

GIMBAL-TRANSFORMATION PROCEDURES

In the rendezvous investigation the acceleration forces acting on the ferry vehicle relative to the space-station target originated in the thrust of the vehicle's rocket along the body x-axis. If the components of the thrust along space axes are to be determined, it is necessary to make an Euler angle transformation opposite to the accustomed transformation of gravity forces to airplane coordinates. The Euler rotation initially chosen was the θ, ψ, ϕ rotation. The body-axis system of the vehicle is shown in figure 2. The transformation procedure utilized is to rotate the body axes through $-\phi$, $-\psi$, and $-\theta$, respectively; thus z rotated toward y, then the new y rotated toward x, and finally the new x rotated toward the twice modified z. The resulting inverse direction-cosine matrix is:

$$\begin{Bmatrix} F_{X,I} \\ F_{Y,I} \\ F_{Z,I} \end{Bmatrix} = \begin{Bmatrix} \cos\theta\cos\psi & \sin\theta\sin\phi - \cos\theta\sin\psi\cos\phi & \cos\theta\sin\psi\sin\phi + \sin\theta\cos\phi \\ \sin\psi & \cos\psi\cos\phi & -\cos\psi\sin\phi \\ -\sin\theta\cos\psi & \sin\theta\sin\psi\cos\phi + \cos\theta\sin\phi & \cos\theta\cos\phi - \sin\theta\sin\psi\sin\phi \end{Bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix}$$

and the instantaneous angular velocities are:

$$\begin{aligned} p &= \dot{\phi} + \dot{\theta}\sin\psi + 0 \\ q &= 0 + \dot{\theta}\cos\phi\cos\psi + \dot{\psi}\sin\phi \\ r &= 0 - \dot{\theta}\cos\psi\sin\phi + \dot{\psi}\cos\phi \end{aligned}$$

from which the Euler angle velocities may be solved by determinants to yield:

$$\dot{\theta} = \frac{q\cos\phi - r\sin\phi}{\cos\psi}$$

$$\dot{\psi} = r \cos \phi + q \sin \phi$$

$$\dot{\phi} = p - \dot{\theta} \sin \psi$$

This Euler array is satisfactory for yaw angles less than 90° but does not permit thrust reversal for speeding up the ferry toward the station, which requires $\psi = 90°$. At $\psi = 90°$, $\dot{\theta}$ and $\dot{\phi}$ (and consequently θ and ϕ) are indeterminate.

The second Euler order chosen to allow ψ to approach 180° is in the order θ, ϕ, ψ. The inverse direction cosine matrix for this $-\psi$, $-\phi$, $-\theta$ transfer is:

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$$\begin{Bmatrix} F_{X,I} \\ F_{Y,I} \\ F_{Z,I} \end{Bmatrix} = \begin{Bmatrix} \cos \phi \cos \psi + \sin \theta \sin \phi \sin \psi & \sin \theta \sin \phi \cos \psi - \cos \theta \sin \psi & \sin \theta \cos \phi \\ \cos \phi \cos \psi & \cos \phi \cos \psi & -\sin \phi \\ \cos \theta \sin \phi \sin \psi - \sin \theta \cos \psi & \sin \theta \sin \psi + \cos \theta \sin \phi \cos \psi & \cos \theta \cos \phi \end{Bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix}$$

and the Euler angle rates are:

$$\dot{\theta} = \frac{q \cos \psi + p \sin \psi}{\cos \phi}$$

$$\dot{\phi} = p \cos \psi - q \sin \psi$$

$$\dot{\psi} = r + \dot{\theta} \sin \phi$$

This transfer limited ϕ to less than 90°, which did not limit rendezvous maneuvering; only pitch and yaw were required for spatial control, since the thrust vector was insensitive to roll. However, this transformation maintained roll about the same body x-axis during changes in yaw and pitch so that as the vehicle heading was changed, the pitch and roll response indicated on the 2-axis 8-ball was interchanged. At $\psi = 90°$, this response was completely interchanged so that pitch attitude required lateral stick motion, and roll attitude required fore or aft controller inputs. This requirement made the vehicle difficult to control, and this procedure was abandoned. This difficulty was believed to be caused by an inconsistency between the Euler angle transformation and the gimbal arrangement in the 8-ball instrument.

The acceleration transfer that proved to be compatible with the instrument gimbals and was used for the tests in the present investigation was the familiar ψ, θ, ϕ order. This Euler transformation did allow nearly 180° yaw-attitude changes and prevented control coupling, but limited θ to less than 90°. The direction cosine matrix is shown in equation (10), and the angular rates in equations (14), (15), and (16).

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In order to overcome the deficiency of the chosen simulator system in pitch, a "gimbal flip" circuit was devised that would allow the vehicle to perform a half-loop and roll-out maneuver to reverse the direction of the thrust rocket. A diagram of the gimbal flip circuit, which operates on the outputs of the servomultipliers in the analog computer is shown in figure 20. As θ approaches 90° (at 88°) the analog voltage representing ϕ and ψ approaches 90 volts and actuates the circuit to "flip" or change ϕ and ψ by 180° in a step manner. The pitch angle never exceeds 90°, and as the physical attitude of the ferry passes 92°, the pitch instrument comes out of the hold mode and retraces from 88° to zero as the ferry completes the half loop to 180° from the initial heading. This procedure works for steady pitch rates through the $\pm 2^{\circ}$ deadband about $\theta = 90^{\circ}$, but the Euler quantities are not computed within this deadband. In actual use the analog portion of the "gimbal flip" network performed satisfactorily, but the instrument servos would not allow the instruments to follow the 180° step input without modification. Time did not permit modification of the instrument servos during the present study, and the rendezvous program was conducted with 180° heading changes made by yawing the vehicle, and θ was limited to less than $\pm 90^{\circ}$; the limitation of the servo drives was a physical problem, however, and it was felt that the "flip circuit" was successful and would serve as a useful simulation tool.

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TABLE 1

INITIAL CONDITIONS FOR RENDEVOUS CASES INVESTIGATED

Case	α, deg	β, deg	$\dot{\alpha}$, deg/sec	$\dot{\beta}$, deg/sec	R, miles	$\dot{R}$, ft/sec	Uncontrolled miss distance, miles
1	45	0	0.0284	0	30	-495	4.7
2	0	-22	0	-.0540	50	-435	28.6
3	20	40	-.0482	0	10	-317	1.4
4	-20	-15	-.0423	-.0315	50	-875	13.9
5	20	-10	-.0600	-.0111	30	-705	7.2
6	20	20	.0775	.0858	30	-4.3	----

TABLE 2

PILOT-OPINION RATING SYSTEM FOR SPACE-RENDEZVOUS MISSION

Adjective rating	Numerical rating	Control characteristics	Mission accomplished
Satisfactory	1	Excellent, includes optimum	Yes
	2	Good, pleasant to fly	Yes
	3	Satisfactory, but with some mildly unpleasant characteristics	Yes
Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes
	5	Unacceptable for normal operation	Doubtful
	6	Acceptable for emergency condition only	Doubtful
Unacceptable	7	Unacceptable even for emergency condition	No
	8	Unacceptable - dangerous	No
	9	Unacceptable - uncontrollable	No
Impossible	10	Did not get back to report	No

L1250

TABLE 3

PILOT-OPINION RATINGS FOR EACH RENDEZVOUS CONFIGURATION

[Numerical system of pilot rating is explained in table 2]

Case (see table 1)	With damping						No damping					
	No misalinement			With misalinement			No misalinement			With misalinement		
	Pilots			Pilots			Pilots			Pilots		
	A	B	C	A	B	C	A	B	C	A	B	C
	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control	Control
1	3	3	3	3	3	4	3	5	5	4	5	6
2	3	2	2	4	4	2	4	4	5	3	5	6
3	3	4	3	4	6	4	4	4	5	5	4	6
4	3	3	2	4	4	4	4	4	4	5	5	6
5	3	3	2	2	2	4	3	3	3	4	5	5
6	3	3	2	4	5	4	4	4	5	4	5	4

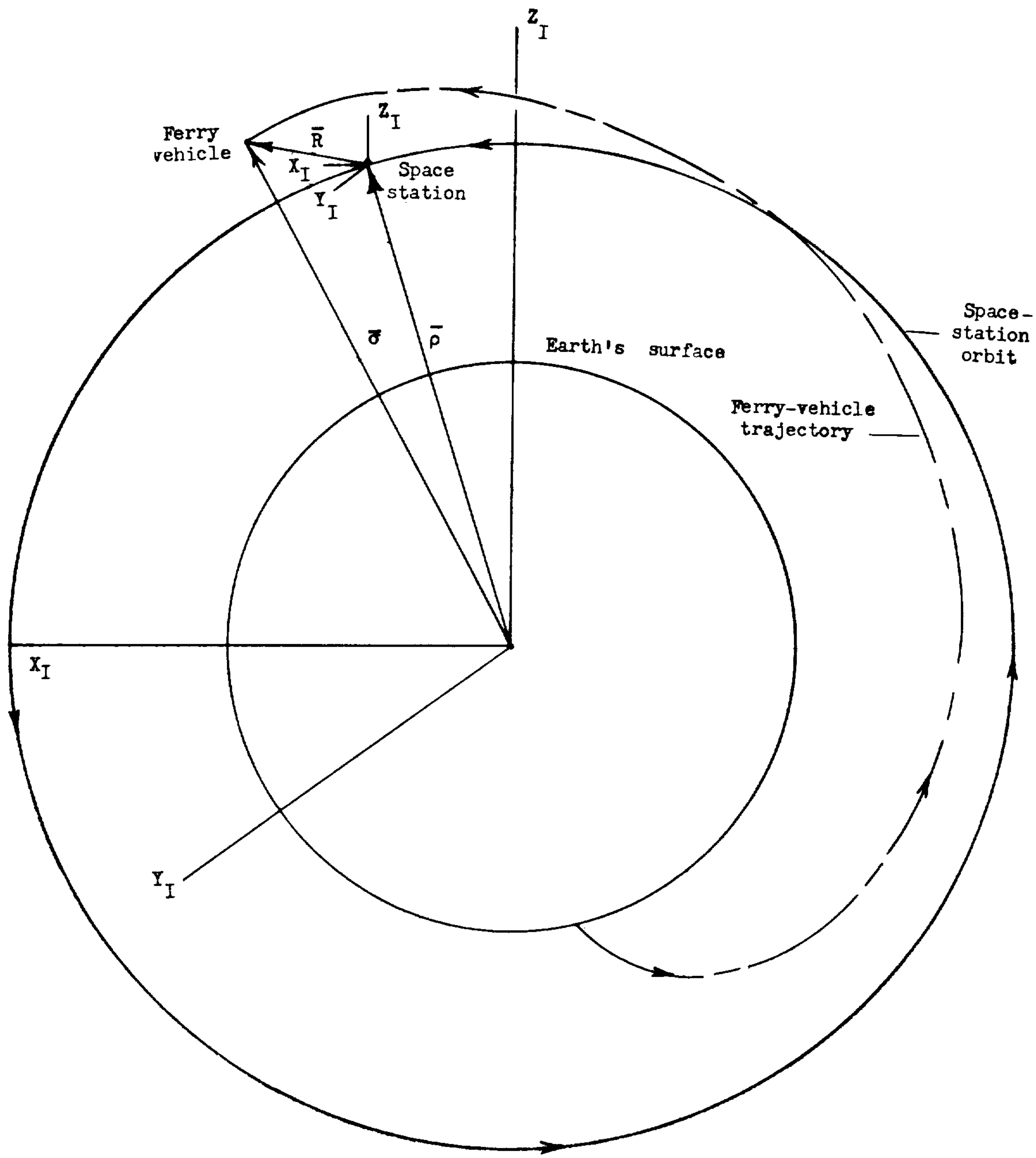


Figure 1.- Trajectory relations between rendezvous vehicle and space station.

L-1250

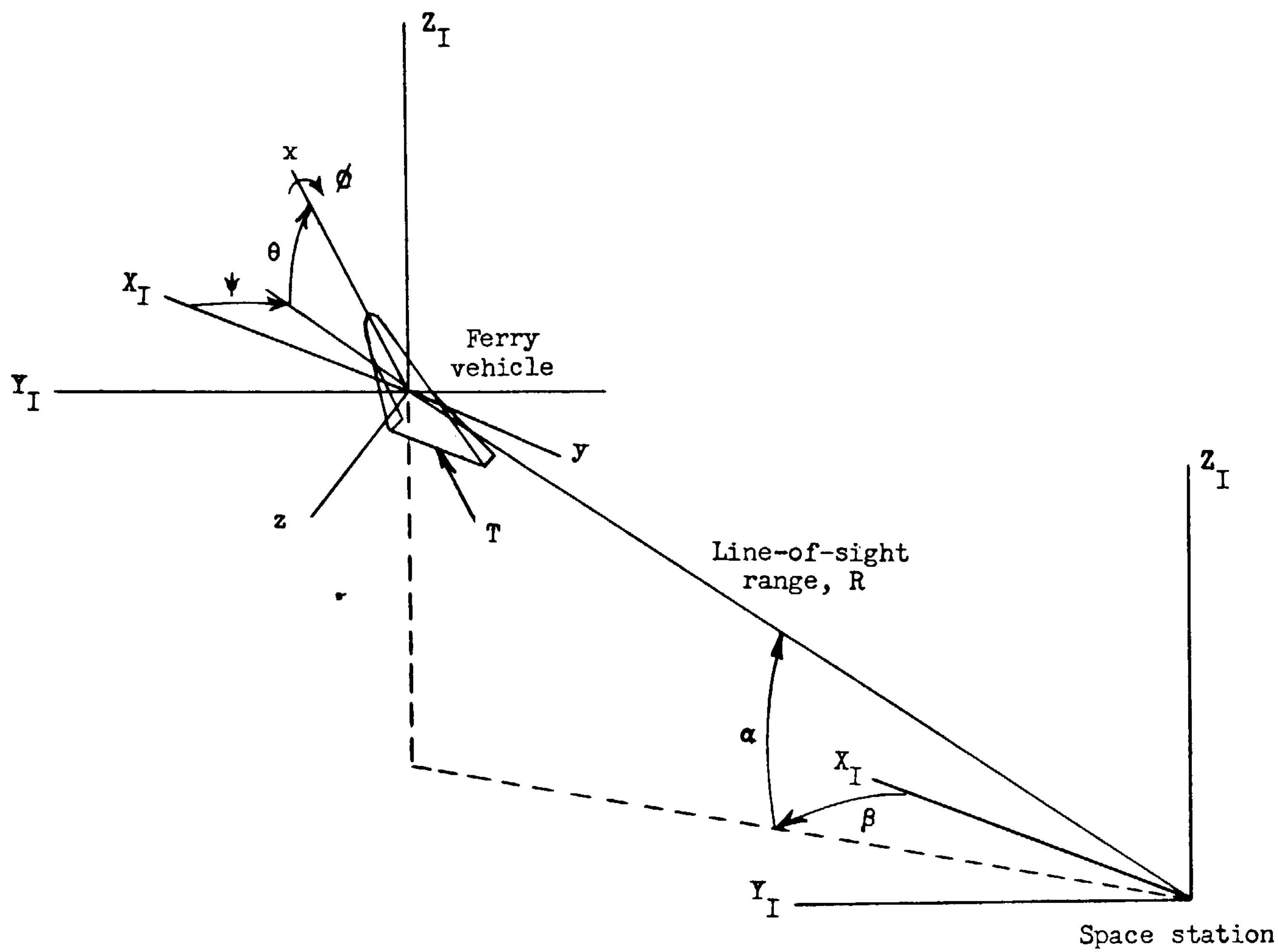


Figure 2.- Line-of-sight and Euler angle relations between rendezvous vehicle and space station.

Figure 3.- Photograph of analog computer and simulator cockpit. L-60-3091

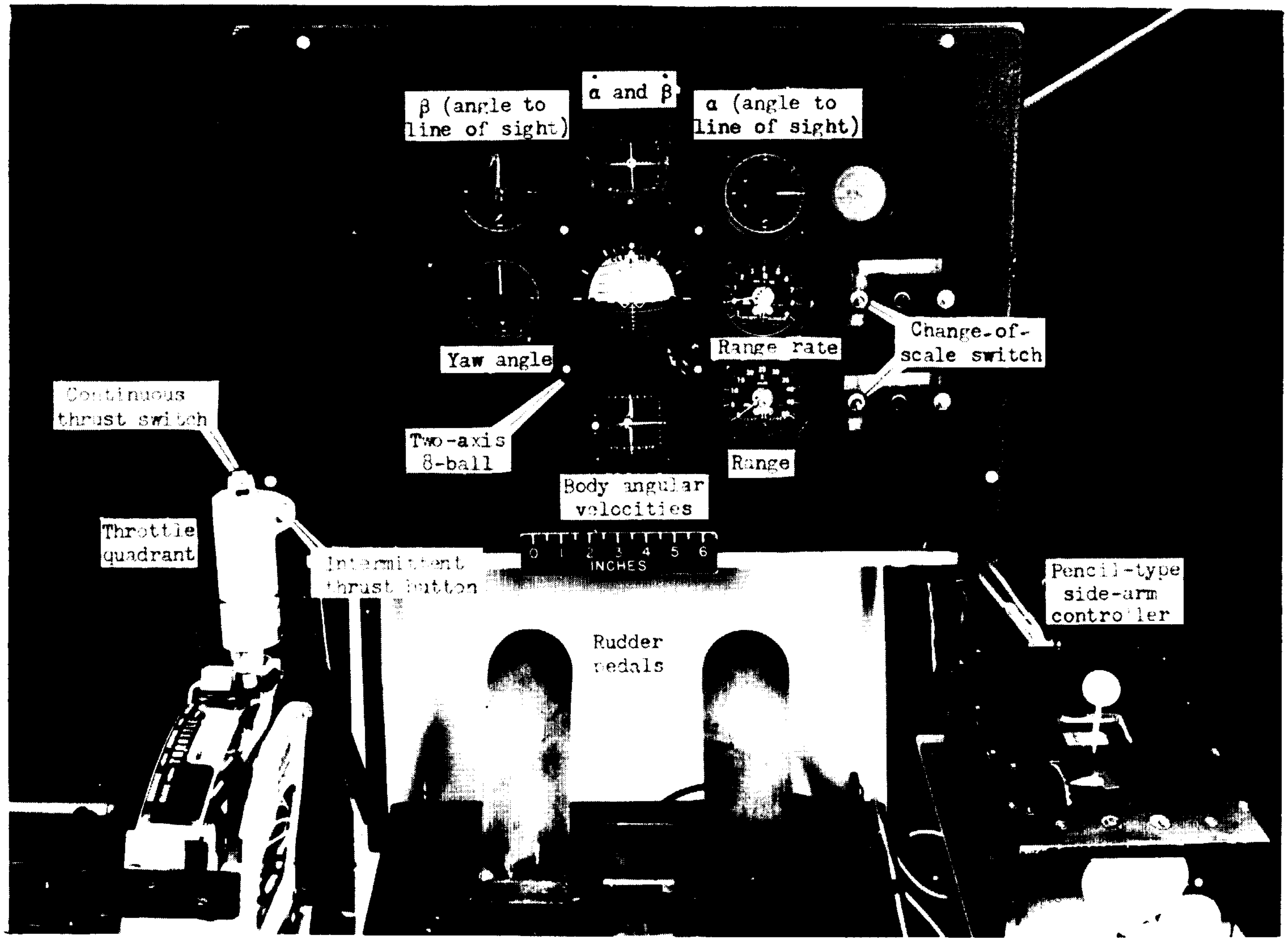


Figure 4.- Photograph of cockpit display. L-60-4266.1

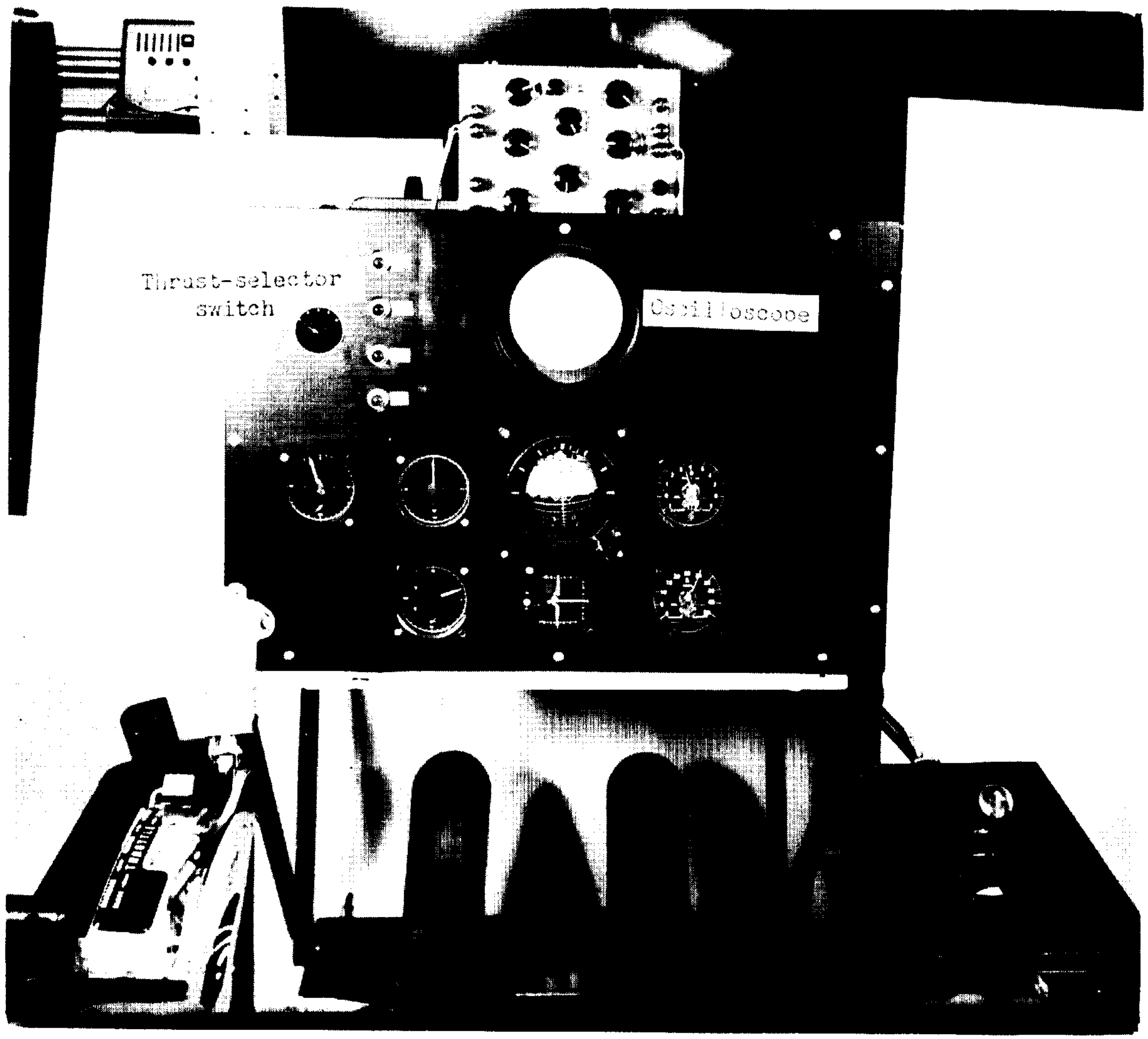
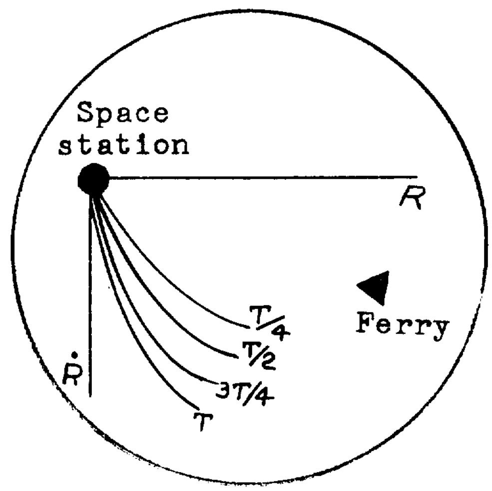
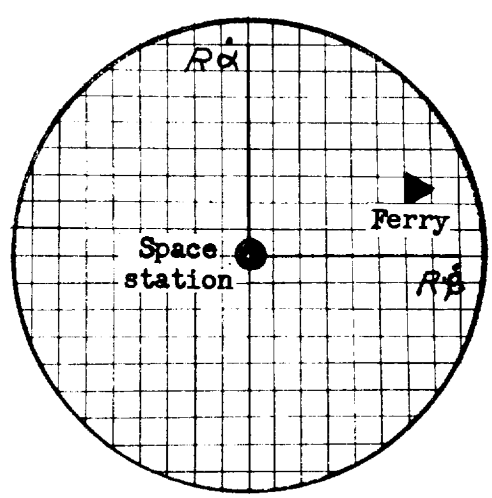


Figure 5.- Instrument panel 1 showing oscilloscope display. L-60-3092

L-1250



(a) Display of $\dot{R}$ plotted against R showing four intercept trajectories in terms of retro-rocket thrust. (Only one trajectory was switched on at a time.)



(b) Station position as a function of $R\dot{\alpha}$ and $R\dot{\beta}$.

Figure 6.- Oscilloscope displays utilized on one version of data panel 1.

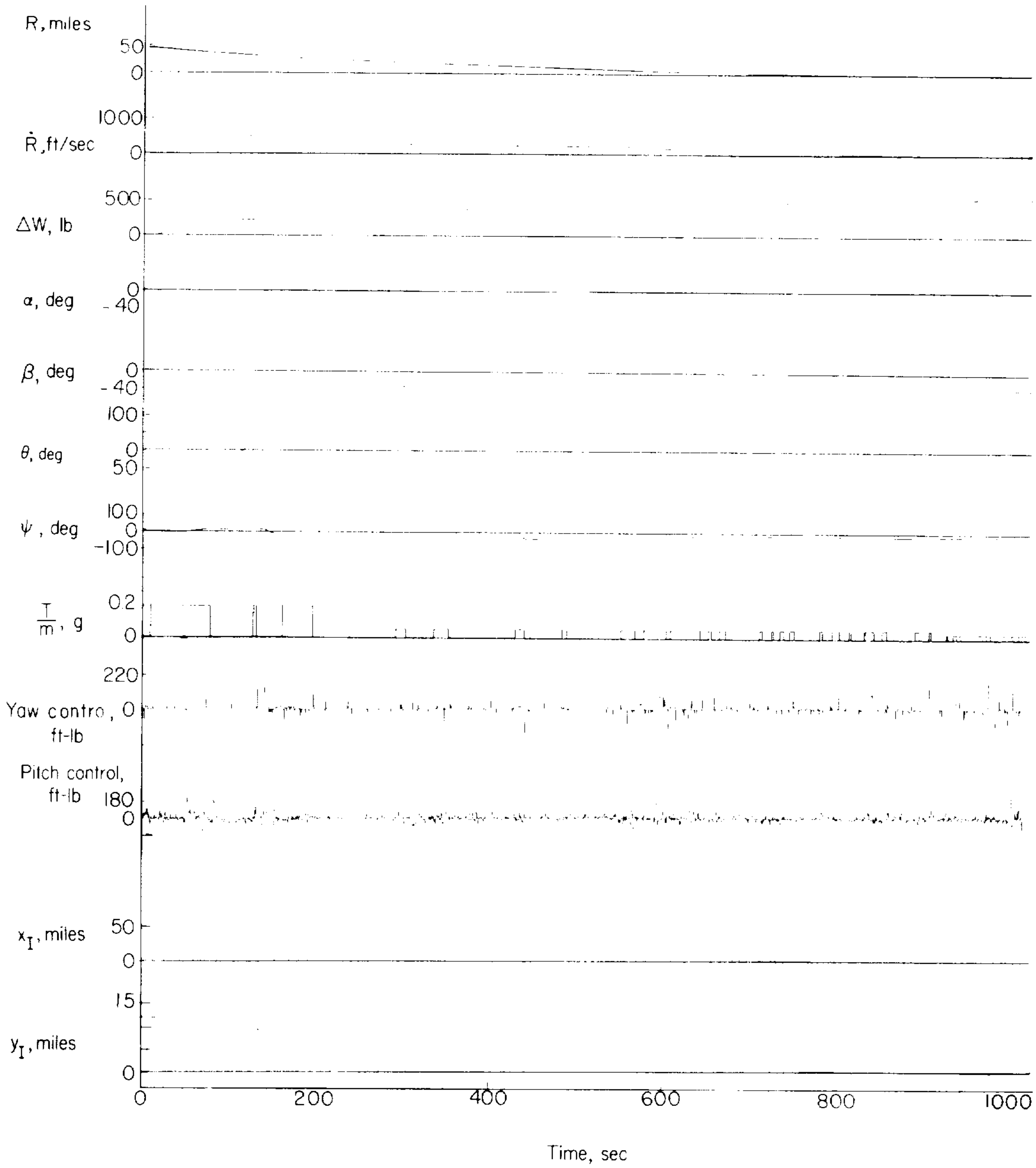


Figure 7.- Time history of a typical rendezvous made with conditions of case 4 ($\tau_x = \tau_y = \tau_z = 10$ sec).

L-1250

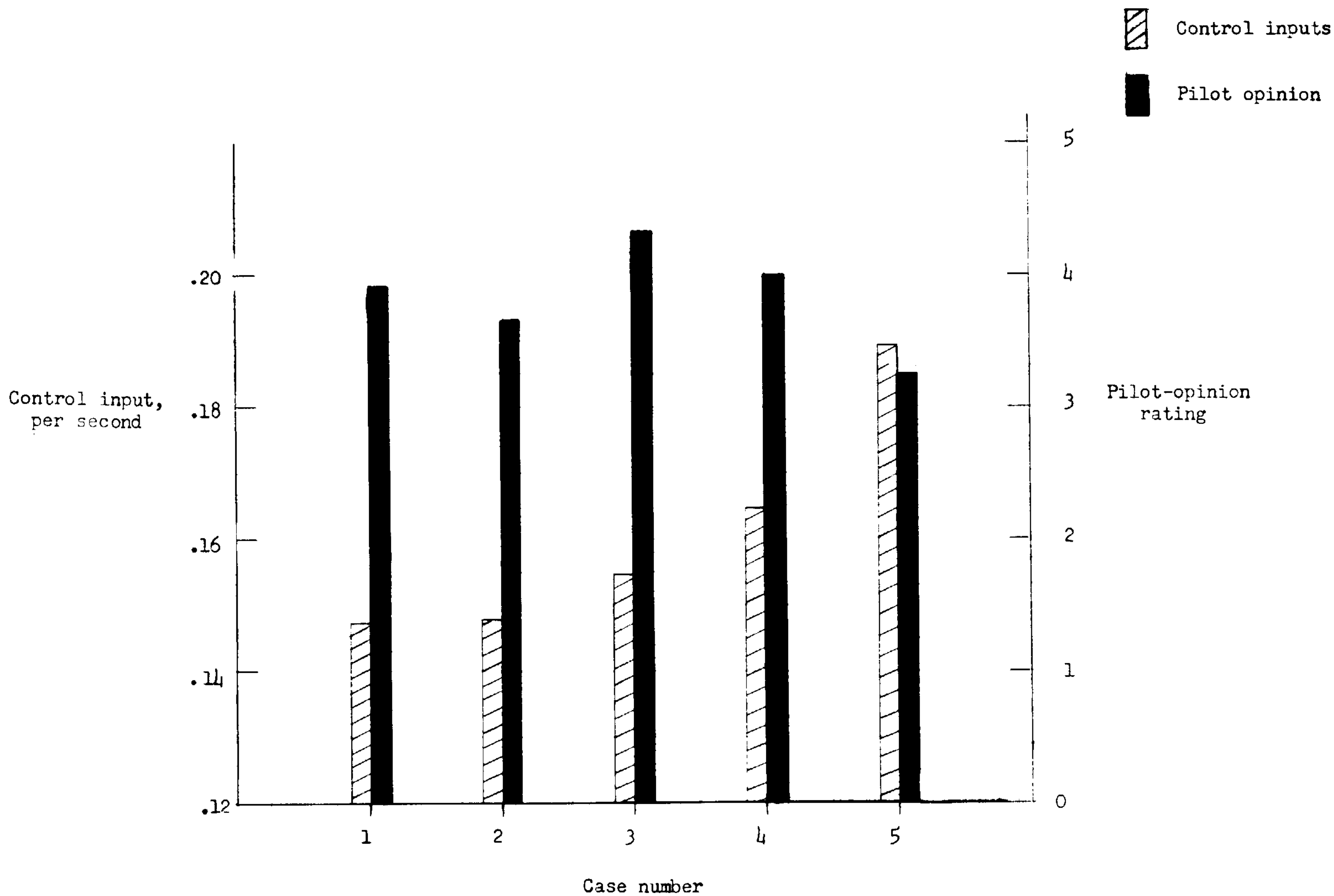


Figure 8.- Bar graph of pilot-opinion ratings and control inputs for all rendezvous cases. (Conditions for each case listed in table 1.)

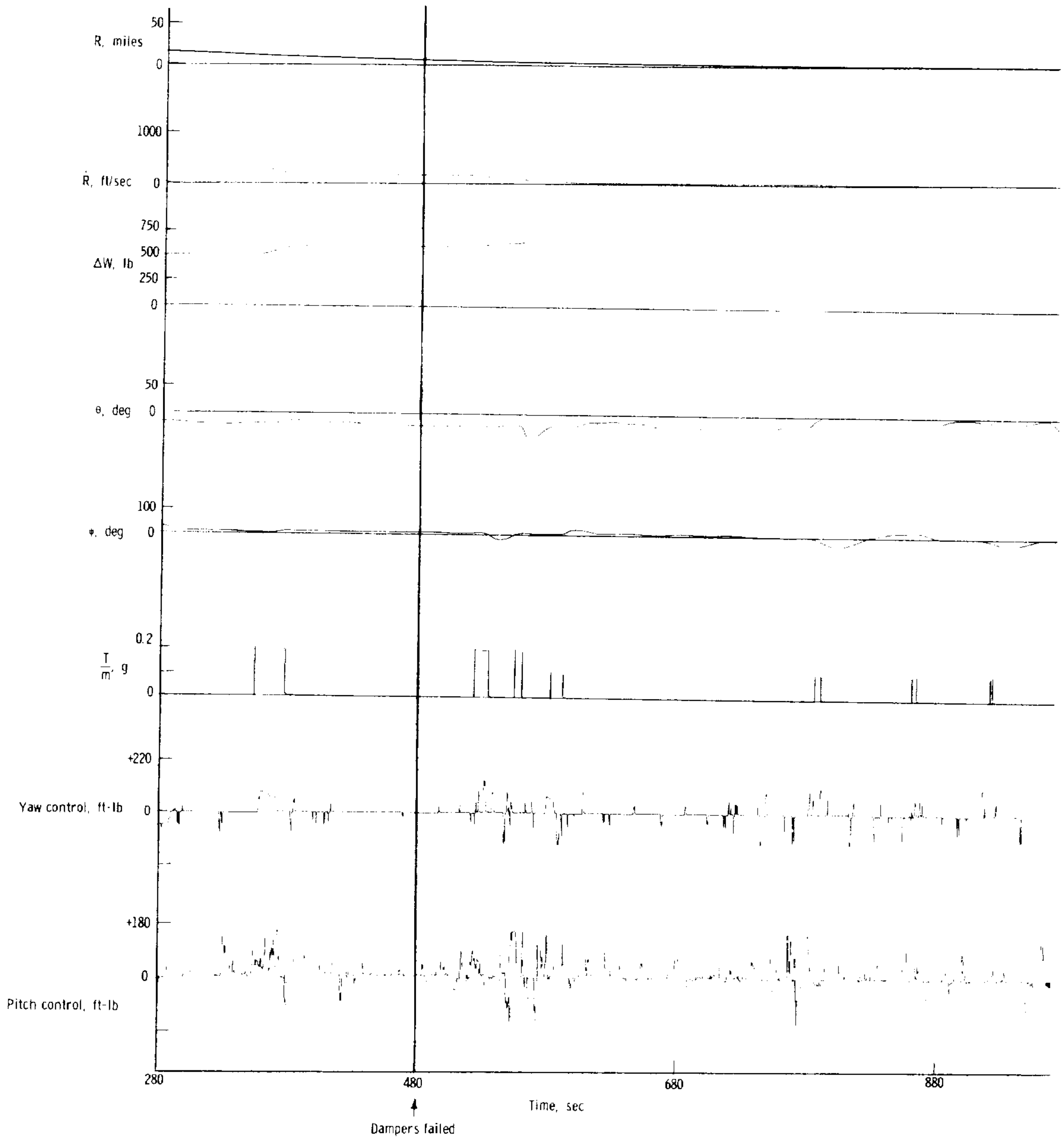
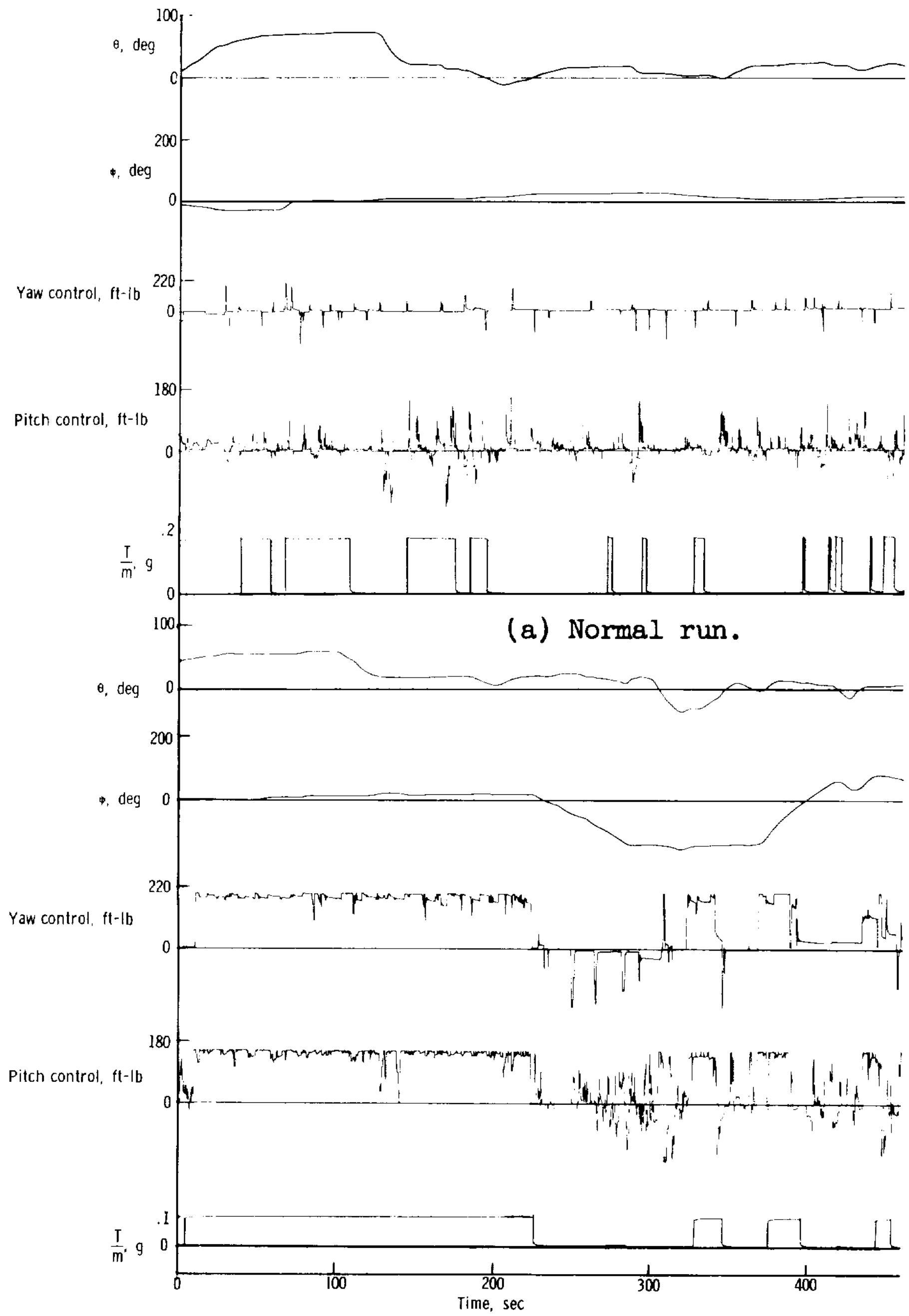


Figure 9.- Time history of a rendezvous showing the effect of damper failure.

L-1250

L-1250



(a) Normal run.

(b) Run with 90-percent misalinement torque.

Figure 10.- Time history of a rendezvous showing the effect of misalinement torque.

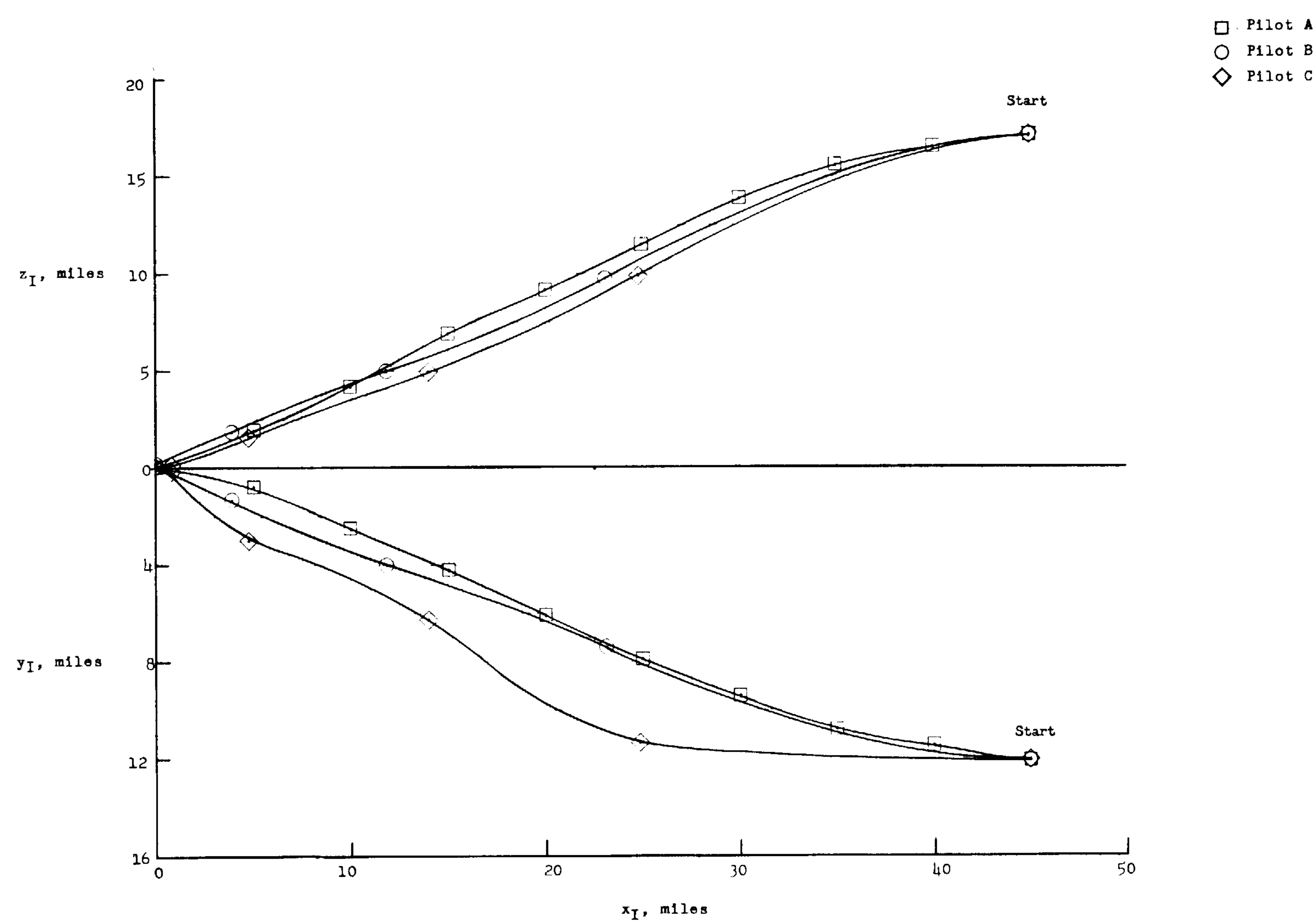


Figure 11.- Position trajectories of pilots for rendezvous conditions of case 4 (table 1).

L-1250

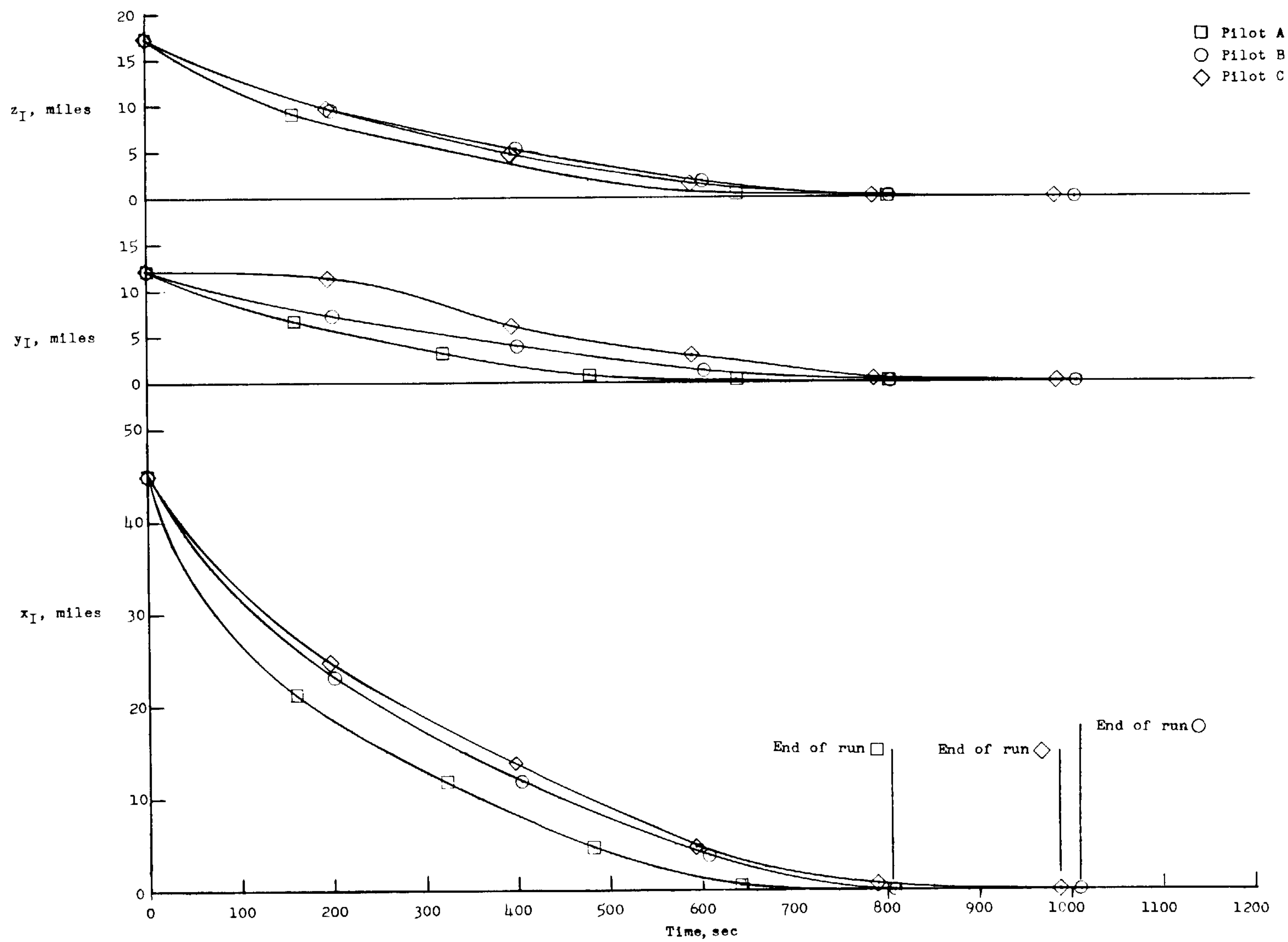


Figure 12.- Position-time trajectories of pilots for rendezvous conditions of case 4 (table 1).

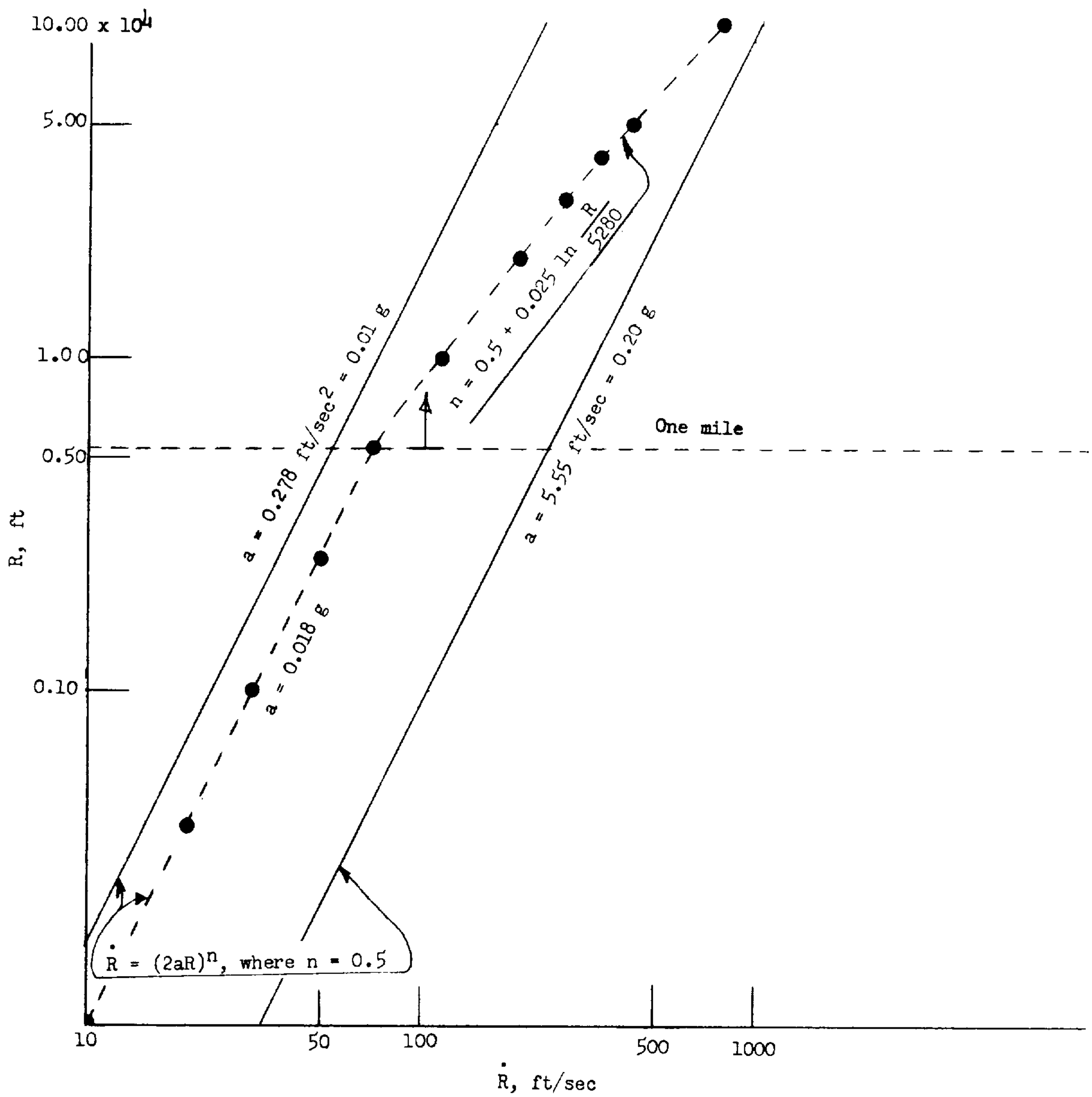


Figure 13.- Energy-management schedule, modified beyond 1-mile range, which was presented to pilots as a table (dashed curve). Constant-acceleration schedules for 0.01g and 0.20g are compared.

L-1250

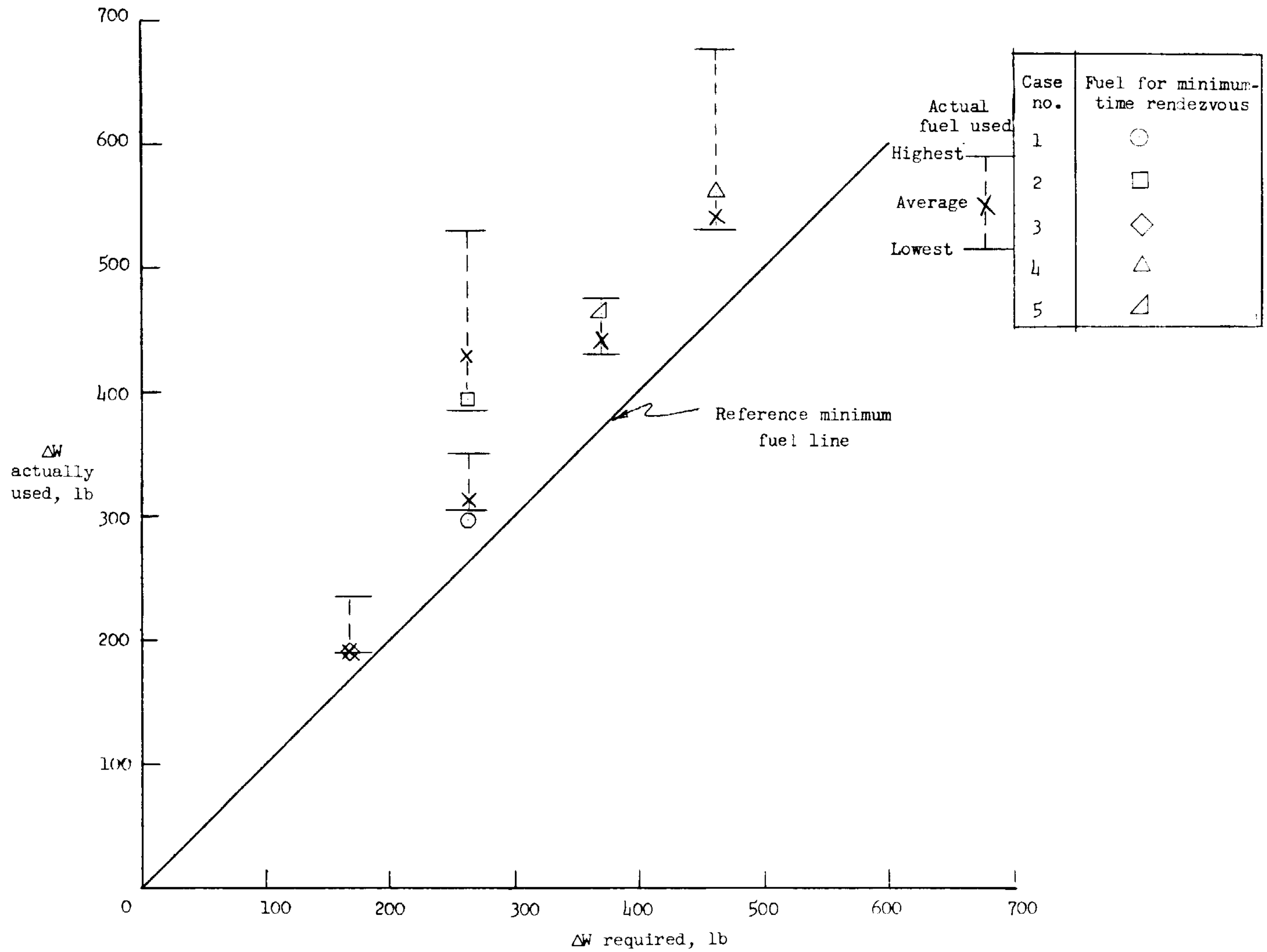


Figure 14.- Weight of fuel used relative to fuel required for rendezvous with cases 1 through 5 (table 1).

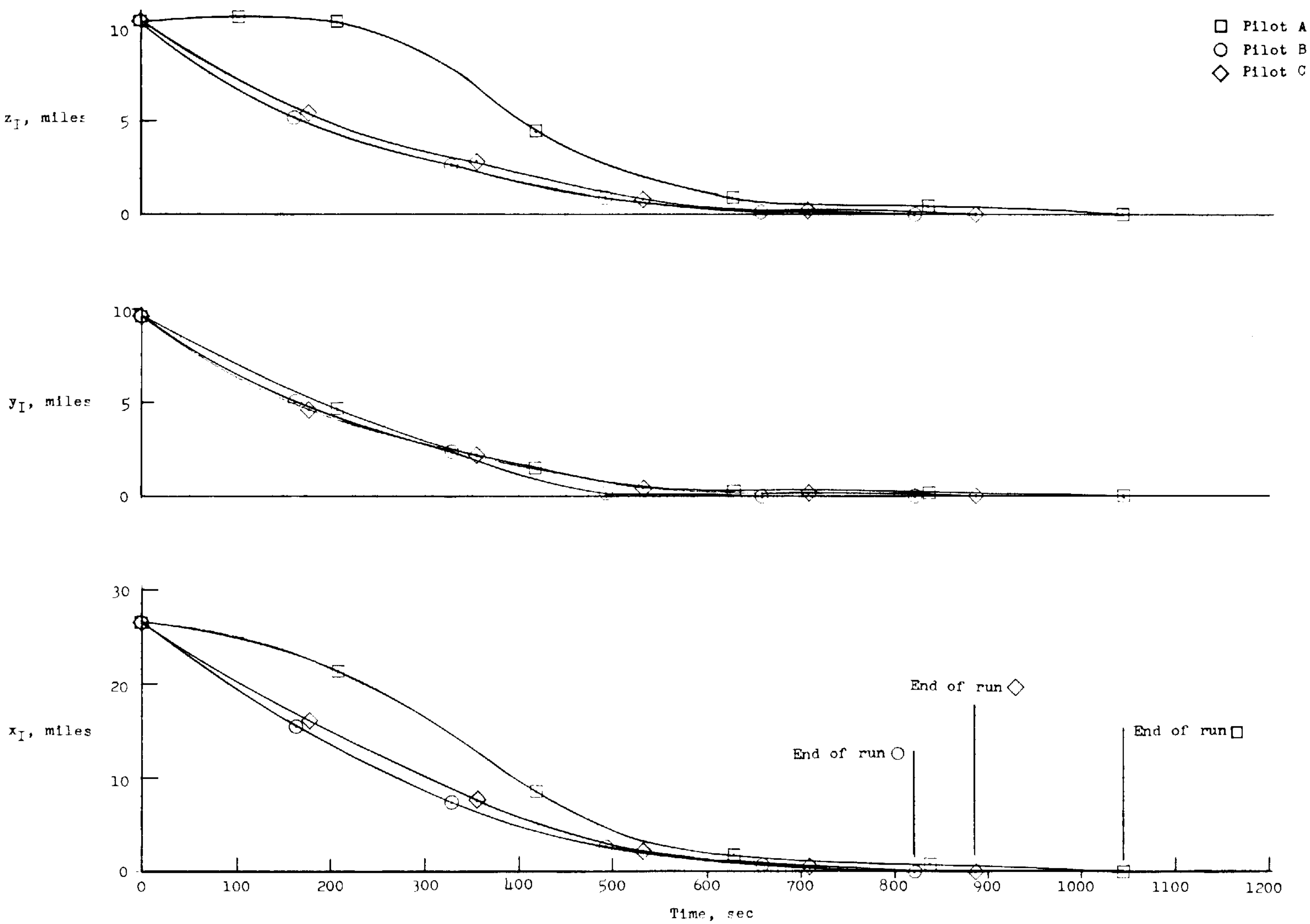


Figure 17.- Position-time trajectories of near-orbital rendezvous (case 6).

L-1250

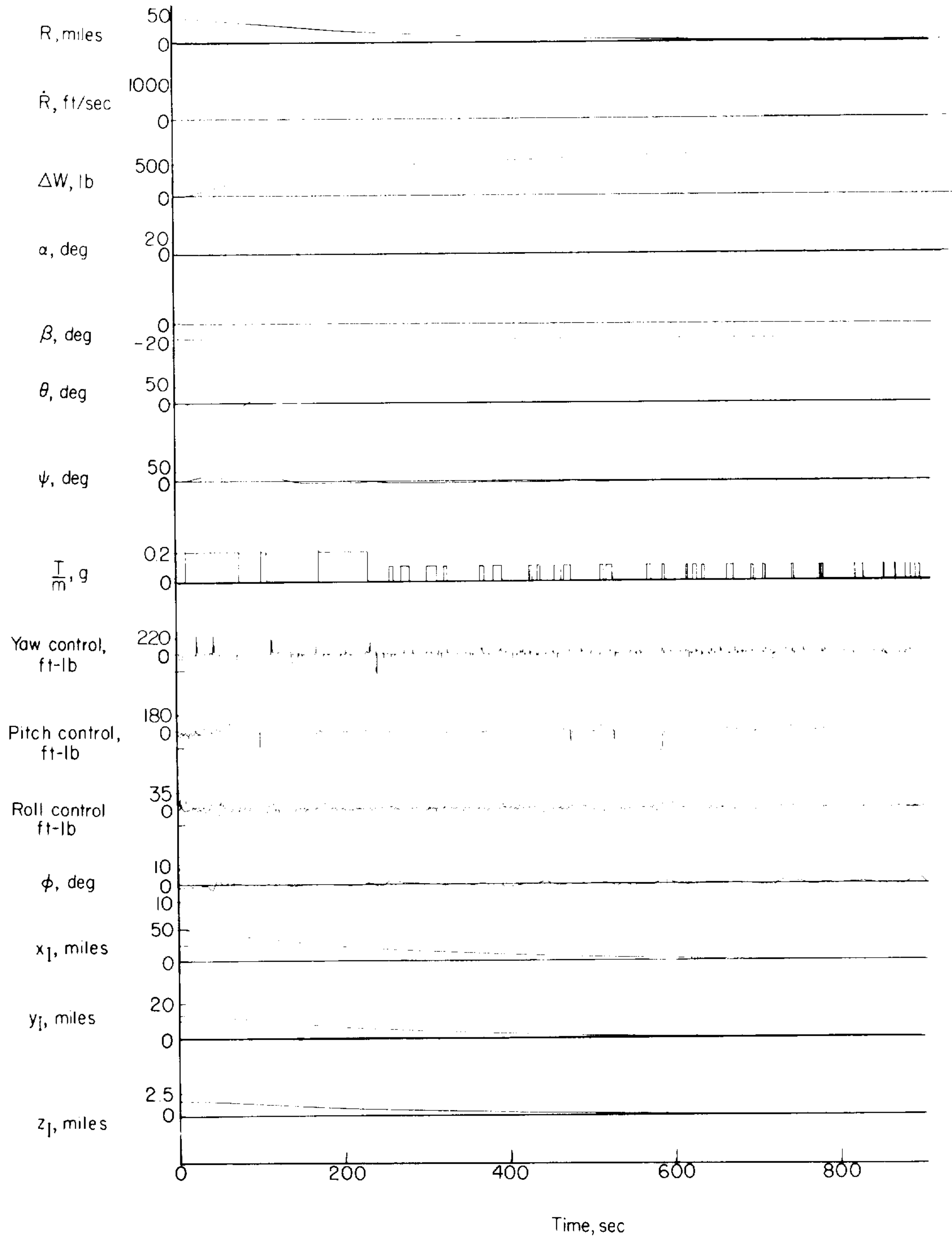


Figure 18.- Time history of a rendezvous made with conditions of case 4 with space station in an elliptical orbit.

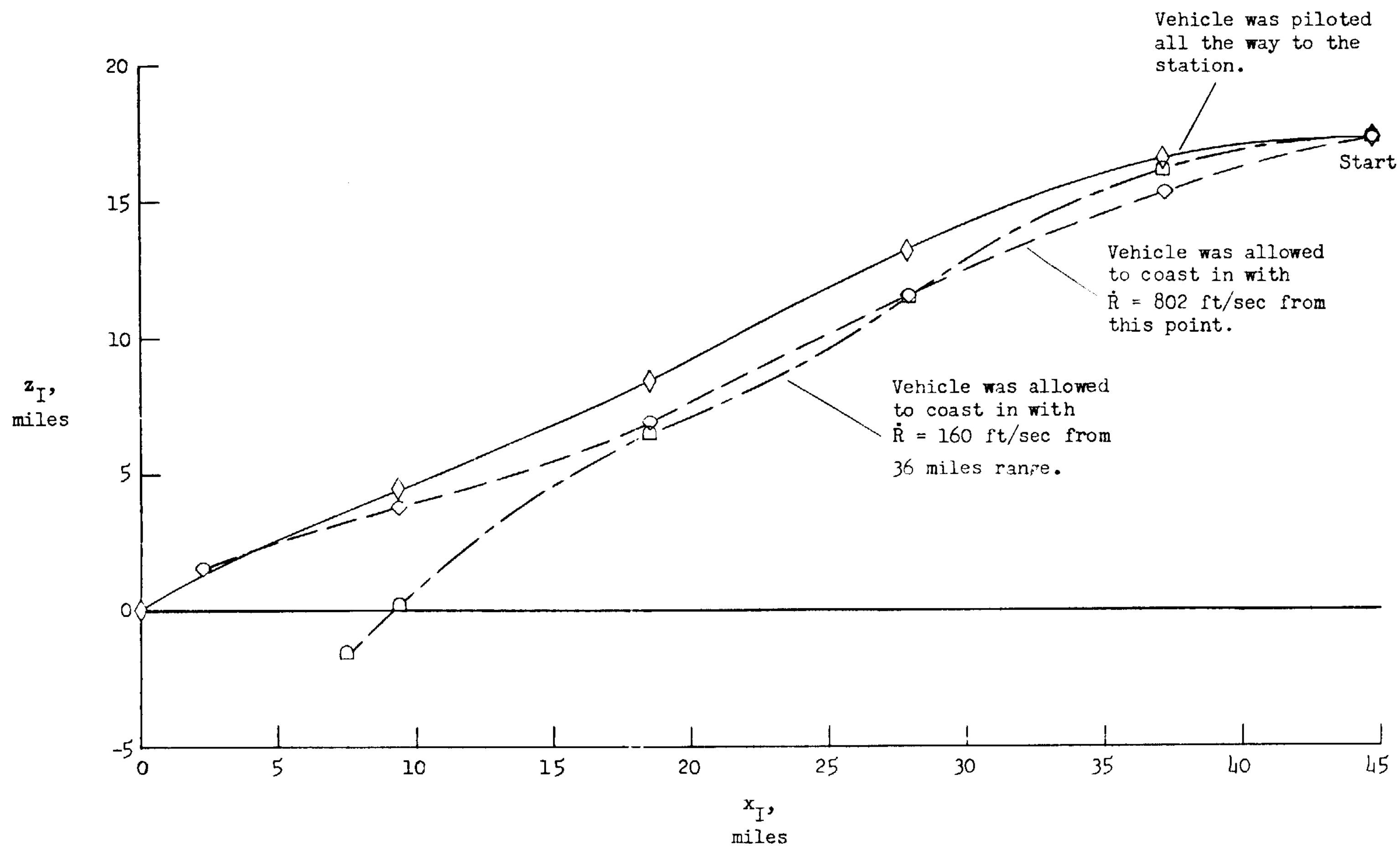


Figure 19.- Trajectories of vehicle showing effects of gravity and orbital ellipticity.

L-1250

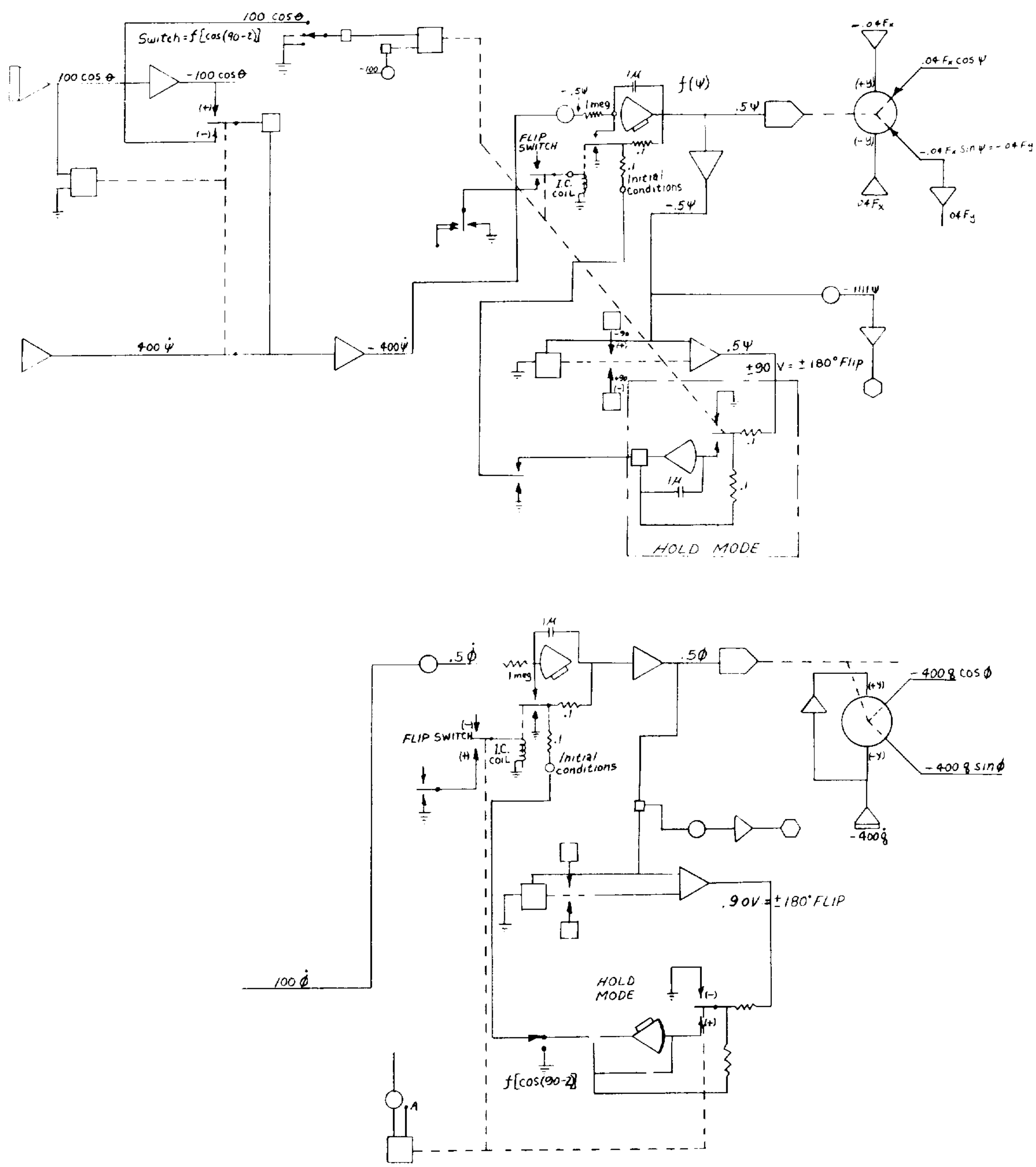


Figure 20.- Gimbal-flip circuits.